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Adaptation, Mitigation and Innovation: A Comprehensive Approach to Climate Policy

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Abstract
The ultimate question that most interests policy makers is how to reduce the climate change vulnerability of socio-economic systems in the most cost-effective manner. Extended literature has investigated the different dimensions of mitigation strategies, whereas much less can be found on adaptation. Even less can be found on the interactions between adaptation and mitigation. The increasing emphasis on adaptation raises a set of still unanswered questions concerning the design of an optimal mix of mitigation and adaptation measures.

This paper presents an Integrated Assessment Model (IAM) that explicitly models the connections between mitigation, climate change impacts and adaptation. Compared to the few existing studies in the field, our framework provides a more detailed characterisation of adaptation processes. Adaptation activities have been distinguished from adaptive capacity building. We also provide an updated quantitative support for the calibration of adaptation costs and benefits. Using this framework, we explore issues such as the optimal timing of mitigation and adaptation, the trade-off between mitigation and adaptation, and the regional distribution of investments and residual damage.

Keywords
Climate change impacts, mitigation, adaptation, integrated assessment model
JEL Codes
Q54, Q56, Q43

AD-WITCH, the model used in this study, has been developed by FEEM in cooperation with the OECD. The contribution of all colleagues who worked to the development of the original WITCH model – in particular Valentina Bosetti, Emanuele Massetti, and Massimo Tavoni – is gratefully acknowledged.

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1. Introduction

Adaptation has become a strategic negotiation item only recently, although the Climate Change Convention has already referred to it in Art. 2 and Art. 4. The difficulty of implementing national and international mitigation policies as well as the increasing awareness of climate inertia eventually put adaptation under the spotlight of science and policy. The EU has recently released the Green Paper on Adaptation[1] and many EU countries have prepared to implement national adaptation plans. The Bali action plan[2] has identified the need for enhanced adaptation action by Parties of the Convention. Adaptation is one of the five key building blocks for a strengthened response to climate change.

The ultimate question that most interests policy makers is how to reduce the climate change vulnerability of socio-economic systems in the most cost-effective manner. This can be achieved through both mitigation and adaptation. It requires on the one hand a thorough knowledge of the size and the regional distribution of damages, and on the other hand a precise assessment of the cost and effectiveness of alternative policies and of their strategic complementarity and trade-offs.

Extended literature has investigated the different dimensions of mitigation strategies, whereas much less can be found on adaptation. Even less can be found on the interactions between adaptation and mitigation. The increasing emphasis on adaptation raises a set of still unanswered questions concerning the design of an optimal mix of mitigation and adaptation measures. Policy insights need to be provided on the optimal resource allocation between mitigation and adaptation, between different adaptation options, and on the optimal timing of mitigation and adaptation. However, as recently observed by Parry (2009), a framework that explicitly models the connections between mitigation, climate change impacts and adaptation is still missing.

The present report addresses these issues using an Integrated Assessment Model (IAM) that has been developed for the joint analysis of adaptation and mitigation. Starting from the WITCH model (Bosetti et al 2006), we have added a new module that captures the links between adaptation and

[1] http://ec.europa.eu/environment/climat/adaptation/index_en.htm
[2] http://unfccc.int/meetings/cop_13/items/4049.php

climate change impacts, yielding the AD-WITCH model. Compared to the few existing studies in the field, our framework provides a more detailed characterisation of adaptation processes. Adaptation activities have been distinguished from adaptive capacity building. We also provide an updated quantitative support for the calibration of adaptation costs and benefits. Using this tool, we analyse several policy issues such as:

- the optimal timing of mitigation and adaptation investments
- the role of adaptive capacity
- the regional distribution of adaptation and mitigation investments
- the trade-offs between adaptation and mitigation
- the regional distribution of residual damages (net of impacts of adaptation)

This report is organised as follows. Section 2 reviews the treatment of climate change damages in existing IAMs. Section 3 introduces the WITCH model. The standard and AD versions of the model are then compared and the calibration process of the AD-WITCH model is carefully described. Section 4 assesses the trade-off between mitigation and adaptation. It addresses the relationship between different adaptation strategies under various policy scenarios. Section 5 presents a sensitivity analysis of our results to different damage values and discount rates. Section 6 concludes and summarises our main results. Three Annexes describe the analytical structure of the model and the re-calibration of the damage function.

2. Climate change damage and adaptation within Integrated Assessment Models (IAMs)

2.1 Integrated Assessment Models: a primer

In its general definition, an Integrated Assessment Model (IAM) is a mathematical tool where the knowledge from different scientific fields is amalgamated to tackle climate change in the most comprehensive way. Due to the multidimensionality of climate change, Integrated Assessment approaches have become the preferred methodology to deal with it. Since the 90’s, IA modelling exercises have boomed. In 1996, 26 of these models were officially acknowledged (Weyant, 1996).

Since then, the number of models including the feedback between the economic and the climatic dimension has quadrupled.

It is beyond the scope of this report to provide an in-depth survey of the different models within the vast family of IAMs (see for example Bosello et al. 1998 and Warren et al., 2006). It is useful to recall the broad distinction between hard-linked and soft-linked IA models, and between policy-optimization and policy-simulation models. Albeit unclear, these categories are still broadly valid. They allow us to contextualize our proposed exercise.

In hard-linked IAMs, the climate and economic dimensions are treated as a "unified" system represented by a consistent set of differential equations. Emissions build CO2 concentrations and temperature. A reasonably refined damage function translates temperature increase into GDP losses. Examples of well known hard-linked models are the RICE model family (Nordhaus and Yang 1996; Nordhaus and Boyer 2000), the MERGE model (Manne and Richels 1995; 2004), and the FUND model (Tol 2002, 2002a).

In soft-linked IAMs, environmental and economic variables belong to two or more separated modelling exercises. They are then connected in sequential chain process: outputs of climate models are inputs to environmental impact modules. The outputs of environmental impact modules are then inputs to economic models, which finally provide an economic assessment. Examples of this kind of exercises are the IMAGE (Bouwman et al. 2006), SGM (Prinn et al. 1998), and AIM (Matuoka et al. 1995) models.

These approaches show symmetric pros and cons: the main advantage of hard-linked models is the internal consistency, which in addition allows researchers to perform full optimization exercises. In other words, the model can replicate the choices of a fully rational, perfectly farsighted, decision-maker. Their major shortcoming is that consistency can be preserved if climate, economics and their links are represented within the same mathematical framework. As a consequence, their description has to be simplified. On the contrary, soft-linked models can provide detailed representations of different domains, but the links between models may show inconsistencies and model optimization may not converge. Along with the computational burden associated to the solutions of a sequence of models, researchers are fully prevented from performing intertemporal optimization exercises because some feedback could not be closed.

The distinction between hard and soft links translates into the distinction between policy optimization versus policy simulation. Policy optimization IAMs perform “normative” exercises: they answer the question on what would be the optimal level of environmental externality based on a cost-benefit analysis. These models are also used to identify the cost-effective portfolio of strategies to reach a given environmental target. Policy simulation IAMs perform more “positive if - then exercises,” by assessing the direct and higher order costs of given environmental policies.

In the next section, we will analyse the problem of the optimal integration and trade-offs between mitigation and adaptation strategies using AD-WITCH, a hard-linked climate-economy model. Our approach will be focused on policy optimisation, even though the game-theoretic structure of WITCH will allow us to deal with second best equilibria and externality-related inefficiencies.

2.2. Modelling climate change damage and adaptation in hard-linked models

Among the many hard-linked models dealing with economic aspects of climate change, some can be considered particularly representative. These models are: the Mendelshon model (Mendelshon et al. 2000); the FUND model (Tol 1999 and subsequent versions); the DICE/RICE model family (Nordhaus and Yang 1996 and Nordhaus and Boyer 2000); the MERGE model (Manne et al. 1995; 2004); and the PAGE model (Hope 2003). They are reviewed and their results are reported by the Stern Review (Stern 2007) and by the IPCC AR4 (Parry et al. 2007). These models can provide a reliable background to describe the mainstream representation of economic damages from climate change in IA models. Their climate change damage functions (*CCDF*) are reported in Table 1.

RICE 96

In the RICE96 model (Nordhaus and Yang, 1996), climate change impacts are expressed as a percentage loss of GDP. This loss is calculated for a global mean temperature increase of 3°C, for different world regions and different impact areas, namely agriculture, energy, sea-level rise and other sectors. Results, especially for developing regions, are largely based on extrapolation of US data with *ad hoc* assumptions.

Impacts are accumulated by category to determine the total loss as a percentage of GDP for each region. Estimated impacts range from a loss of 0.72% of GDP for landlocked states with no agriculture, to above -4% of GDP for countries with a great deal of coastal activity and a large part of the economy in agriculture. This allows Nordhaus and Yang (2000) to calibrate regional parameters $\theta_{1,i}$ in equation (1), which represent the share of regional income loss compared to the benchmark temperature increase of 3°C. Parameter θ_2 is instead set to 2 to reflect a non-linear (quadratic) nature of damages[3].

Table 1: Examples of climate change damage functions in IAMs

RICE 96 (Nordhaus and Yang 1996)	$CCD_i(t) = 1 - \dfrac{1}{1+\theta_{1,i} \cdot (T(t)/3)^{\theta_2}}$ (1)
RICE 99 (Nordhaus and Boyer 2000-)	$CCD_i(t) = 1 - \dfrac{1}{1+\theta_{1,i} \cdot T(t) + \theta_{1,i} \cdot T(t)^2}$ (2)
MERGE (Manne et al., 1995)	$MCCD_i(t) = \theta_{1,i} \cdot \dfrac{T(t) - T(t=2000)}{2.5}$ (3) $NMCCD_i(t) = \dfrac{T(t) - T(t=2000)}{17.7}$ (4)
PAGE (Hope, 2003)	$CCD_{i,s}(t) = \left(\dfrac{I_{i,s}(t)}{2.5}\right)^{\gamma} \cdot w_{i,s} \cdot \left(1 - \dfrac{IMP_{i,s}(t)}{100}\right)$ (5) $CCDT_i(t) = \sum_s CCD_{i,s}(t) + WIDIS$ (6)
FUND (Tol, 2002 and 2002a)	These two models propose "sector" specific climate change damage functions (see text)
Mendelsohn, (2000)	

RICE 99

[3] In other versions of the RICE 96 model, calibration is performed respect to a 2.5°C temperature increase respect to preindustrial levels and the coefficient is set to 1.5.

In RICE 99 and subsequent model version (Nordhaus and Boyer 1999, 2000), the calibration of the CCDF is similar to that of RICE 96, but slightly more sophisticated and richer in data. First, climate change impacts as a percentage of GDP referred to 1995 are based on two hypothetical scenarios of temperature increase, 2.5°C and 6°C. Calibration is done for the different model regions and "categories of impact": agriculture, sea-level rise, other market sectors, health, non-market amenity, human settlements and ecosystem, catastrophic events. Second, impacts are projected to 2100 assuming an income adjustment factor. This factor is the ratio between future and 1995 income to the power of an estimated income elasticity, or conjectured when quantitative evidence is lacking. Third, impacts are summed across "impact categories" to create overall impact indices of a percentage GDP loss for each region. Finally, a system of two quadratic equations (2) is solved for each region to obtain the damage coefficients. The equations go through three points for temperature change: 0°C, 2.5°C and 6°C.

MERGE

In the MERGE model (Manne et al. 1995 and 2004), climate change produces both market and non-market damages. In the case of market damages, parameters in function (3) are calibrated assuming that a 2.5°C temperature rise would lead to GDP losses of 0.25% in the high income countries and of 0.50% in the low income countries. These figures are extrapolation from the existing literature and should be comprehensive of all kinds of market damages. For higher or lower temperature levels, market losses are assumed to be proportional to the change in mean global temperature from the year 2000. Non-market damages include impacts on human health, species losses and deterioration of environmental quality. In the case of developed countries, function (4) conjectures that expected losses increase quadratically with temperature rise compared to year 2000. Then it is calibrated on the assumption that to avoid a 2.5°C temperature rise, developed countries would be willing to give up 2% of their GDP, the current U.S. total expenditure on all forms of environmental controls. This calibration procedure directly provides the 17.7 figure in (4) which represents the "catastrophic temperature value" at which the entire regional product would be wiped out.

PAGE

In the PAGE model (Hope 2003), the parameters of the CCDF (5) are calibrated to replicate a damage resulting between a 2% loss and a 0.1% gain of world GDP. This occurs when temperature exceeds by 2.5°C, a "tolerable" temperature level that by default is set to 2°C.

Damages are specified regionally and for two “impact sectors”: an economic and a non economic one.

Some features of PAGE’s CCDF are quite interesting. First, a “discontinuity” damage is considered. A factor WIDIS comes into play when temperature levels exceeds 8°C to mimic catastrophic events whose probability increases on average by 10% for each subsequent 1°C temperature rise. Second, damages are an uncertain power function of temperature rise. Third, and more interestingly for our purposes, it considers explicitly adaptation. This operates in three ways: increasing the slope of the tolerable temperature profile and its plateau through the I parameter, and decreasing the adverse impact of climate change when the temperature eventually exceeds the tolerable threshold through the IMP parameter. The “default” adaptation strategy of the model for instance estimates a costs for the economic sector in the EU of US$ 3, 12 and 25 per year (min., mode and max. respectively) to increase by 1°C the temperature tolerability and of additional US$ 0.4, 1.6, 3.2 Billion per year to achieve a 1% reduction in climate change impacts. At the world level this implies, at a discount rate of 3%, a cost of nearly US$ 3 Trillion to achieve a damage reduction of roughly US$ 35 Trillion within the period 2000-2200. Impact reduction ranges from 90% in the OECD to 50% elsewhere. However it is worth noting that in the PAGE model adaptation is imposed exogenously and not determined by the model optimisation process. With the given assumptions, PAGE could easily justify aggressive adaptation policies, thus implicitly decreasing the appeal of mitigation.

The FUND and the MENDELSOHN models

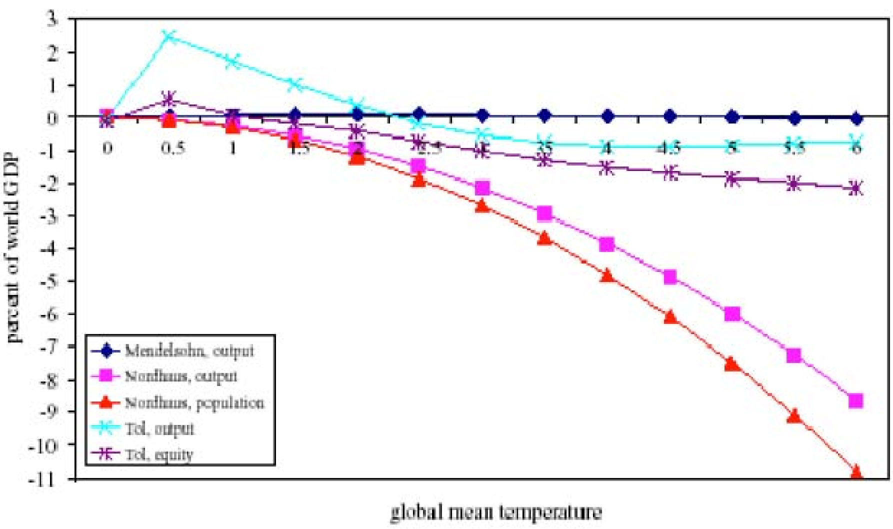
The FUND (Tol, 1999, 2002 and 2002a) and Mendelsohn (Mendelsohn et al. 2000) models are fairly similar as for the specification of climate impacts. Both specify a sector-specific CCDF for each of the economic sectors or impact areas that the models consider.

Climate change costs in agriculture, forestry, water, energy consumption, sea-level rise, ecosystems, vector-borne, and heat and cold-stress related diseases are assessed in the FUND model. In some cases, like that of sea-level rise, damages are assumed roughly linear in temperature increase. In other cases, like those of health, they are not. Nonlinearities and different dynamics of climate damages are impact-specific and not a unique assumption is imposed to the evolution of different damage types. In addition, each CCDF is implemented separately in the model that accordingly computes either the total amount of CCD or that related to each of its different components.

A similar approach is followed by the Mendelsohn model. Impact areas considered are: agriculture, forestry, coastal resources, energy and water. For each of them, a complex reduced form equation specifies the welfare losses or the potential gains as a function of climatic variables (temperature, precipitation, CO2 concentration), physical variables (sea level rise, land areas, lengths of coastline), and economic variables (GDP growth, agricultural GDP growth, land values).

The Mendelsohn model computes damages for 178 world countries. However, the parameterisation of the reduced form CCDF are based on extrapolations from US data and estimates are proposed for market damages only.

Figure 1: Climate change damage functions in the literature



Source: IPCC AR4

As shown in Figure 1, the economic assessment of climate change impacts largely differs among models. Different assumptions regarding the role of adaptation, non-market damages, the risk associated to catastrophic events and different functional specifications of the damage function determine different outputs. For instance, the Mendelshon model appears particularly optimistic because it assumes cheap and effective adaptation in the agricultural sector. The Nordhaus models show higher climate change costs because it includes impacts of catastrophic events. The assessment of climate damages based on FUND falls in between.

Climate change is not uniform throughout the world and its impacts are diverse and highly differentiated by regions. Regions also differ for their intrinsic adaptive capacity. These dimensions, determine a highly differentiated regional vulnerability to climate change. The global picture can provide only a partial and potentially misleading insight on the true economic cost of climate change. Aggregation can conceal vulnerability and climate change costs "hot spots" as depicted in Table 2. As a rule, developing countries would be more affected than their developed counterparts.

Notwithstanding the differences in results, driven by different model specifications, modelling approaches and underlying assumptions, Table 2 highlights the following messages:

- Even an almost null aggregate loss potentially experienced by the world as a whole, and associated to a moderate climatic change, entails high costs for some regions. It is even more so in the case of moderate to high aggregate economic losses;
- There is a clear "equity-adverse" effect from the distribution of climate change impacts. Higher costs are experienced by developing regions that are already facing serious challenges to their social economic development. Within a country or region, climate change adverse effects hit more severely weaker social groups which are both more exposed and less able to adapt.

What is true at the world level applies at the regional level as well. Even a net gain for a region compounds both positive and negative effects. Some of these negative effects can be particularly damaging also for a developed region. Think for instance to an increase in mortality due to more frequent and intense heat waves affecting the aged population. Consider the loss of coastal areas due to sea-level rise. Additionally, hydro-geological risk would be amplified due to an increase in frequency and intensity of extreme weather events. Table 2 summarises the damage estimates for a 2.5°C increase in global temperature above its 1900 level, both for the whole economy (Total) and broken down by sectors, as estimated in Nordhaus and Boyer (2000).

Table 2. Climate change impacts in different world regions under a 2.5°C increase in global temperature above its 1900 level

Region	TOTAL	Agriculture	Other vulnerable market	Coastal	Health	Non-market time use	Catastrophic	Settlements
United States	0.45	0.06	0	0.11	0.02	-0.28	0.44	0.1
China	0.22	-0.37	0.13	0.07	0.09	-0.26	0.52	0.05
Japan	0.5	-0.46	0	0.56	0.02	-0.31	0.45	0.25
EU	2.83	0.49	0	0.6	0.02	-0.43	1.91	0.25
Russia	-0.65	-0.69	-0.37	0.09	0.02	-0.75	0.99	0.05
India	4.93	1.08	0.4	0.09	0.69	0.3	2.27	0.1
Other high income	-0.39	-0.95	-0.31	0.16	0.02	-0.35	0.94	0.1
High-income OPEC	1.95	0	0.91	0.06	0.23	0.24	0.46	0.05
Eastern Europe	0.71	0.46	0	0.01	0.02	-0.36	0.47	0.1
Middle-income	2.44	1.13	0.41	0.04	0.32	-0.04	0.47	0.1
Lower middle-income	1.81	0.04	0.29	0.09	0.32	-0.04	1.01	0.1
Africa	3.91	0.05	0.09	0.02	3	0.25	0.39	0.1
Low-income	2.64	0.04	0.46	0.09	0.66	0.2	1.09	0.1
Global								
Output-weighted	1.5	0.13	0.05	0.32	0.1	-0.29	0.17	1.02
Population-weighted	2.19	0.17	0.23	0.12	0.56	-0.03	0.1	1.05

Source: Nordhaus and Boyer (2000)

Among rich countries, Europe is estimated to suffer the most from climate change, because of the assumption of high vulnerability to catastrophic events. Among developing regions, Africa and India face larger climate impacts due to impacts on health and catastrophic events, respectively. Impacts on agriculture vary a lot with the climatic conditions of the regions and become positive for cold or mild regions such as Russia and China. Similar patterns can be identified for the impact on energy use, with cold regions such as Russia being more positively affected.

All models considered, excluding the PAGE model, do not explicitly model adaptation. Adaptation is implicitly assumed as one of the component of climate change costs, together with the residual damage. The reduced form CCDF of these models and its parameterisation thus include adaptation. In the PAGE model, adaptation appears explicitly, but is decided at the outset. Accordingly, mitigation and adaptation cannot be compared in the optimising framework.

Adaptation is not explicitly modelled and endogenised in the WITCH model (Bosetti et al. 2006), whose damage function builds upon Nordhaus and Boyer (2000). The first objective of our research work has been to explicitly model adaptation as a choice variable and to separate its cost and benefits from the residual damage component.

3. Incorporating adaptation in the WITCH model

3.1 The WITCH model

The WITCH – World Induced Technical Change Hybrid – model developed by the climate change research team at FEEM (Bosetti et al., 2006; Bosetti et al., 2007) is a hard-linked, energy-economy-climate model designed to deal with the main features of climate change (see also Annex III of this report).

The world economy is disaggregated into twelve macro regions: USA (United States), WEURO (Western Europe), EEURO (Eastern Europe), KOSAU (Korea, South Africa, Australia), CAJAZ (Canada, Japan, New Zealand), TE (Transition Economies), MENA (Middle East and North Africa), SSA (Sub-Saharan Africa), SASIA (South Asia), CHINA (China and Taiwan), EASIA (South East Asia), LACA (Latin America, Mexico and Caribbean). This grouping has been determined by economic, geographic, resource endowment and energy market similarities. The optimisation period covers the century until 2100.

WITCH considers explicitly the noncooperative nature of international relationships. Regions interact with each other through the presence of economic and environmental global externalities. Hence, forward-looking regional planners maximise their own intertemporal welfare taking into account the interactions with other regions (open-loop Nash solution). A cooperative solution can also be implemented in which a world central planner internalises all externalities by maximising the weighted sum of regional utilities.

The model proposes a bottom-up characterisation of the energy sector. Seven different energy-generating technologies are modelled: coal, oil, gas, wind & solar, nuclear, electricity, and biofuels. The model includes two breakthrough technologies whose penetration rate is driven by innovation. It distinguishes dedicated R&D investments for enhancing energy efficiency from investments aimed at facilitating the competitiveness of innovative low carbon technologies in both the electric and non-electric sectors (backstops). R&D processes are subject to stand on shoulders as well on neighbouring effects. Specifically, international spillovers of knowledge are accounted to mimic the flow of ideas and knowledge across countries. Finally, experience processes through Learning-by-Doing are accounted for in the development of niche technologies such as renewable energy (Wind&Solar) and the backstops.

The environmental dimension is accredited for by a climate module that links greenhouse gas (GHG) emissions to GHG concentrations, and lastly to the global mean temperature. A damage function translates the temperature increase in regional GDP losses.

Through the optimisation process regions choose the optimal dynamic path of different investments, namely in physical capital, in R&D and energy technologies. Recently, the WITCH model has been updated with more recent data. It has revised estimates for future projection of the main exogenous drivers. Socio-economic, energy and environmental variables have been re-calibrated to the year 2005 (Bosetti et al. 2009). The AD-WITCH model has been developed starting from this re-calibrated version of WITCH.

3.2 WITCH and AD-WITCH

The specification of the damage function of the WITCH model follows closely Nordhaus and Boyer (2000). Similarly to DICE and RICE, adaptation is implicitly included in the calibration process and climate change damages are a combination of protection costs and residual damages.

A goal of the AD-WITCH model is to separate these two components, following the research line initialised by Bosello (2008) and de Bruin et al.(2009). They have addressed the same issue in the FEEM-RICE and in the RICE-DICE models respectively. The novel contribution of the AD-WITCH model is twofold. First, it integrates in a unitary framework the different adaptation activities that until now has been the object of different studies, namely reactive and proactive adaptation. Second and most importantly, it explicitly accounts for the role of adaptive capacity building in enhancing the effectiveness of adaptation activities. The IPCC defined adaptive capacity as “the ability of a system to adjust to climate change (including climate variability and extremes) to moderate potential damages, to take advantage of opportunities, or to cope with the consequences” (Parry et al. 2007). Adaptive capacity is vital for effective adaptation responses. It contributes to determine the vulnerability of a system and the final impacts of climate change. AD-WITCH decomposes the total climate bill into five components: mitigation, expenditure in total adaptive capacity building (generic and specific), reactive adaptation, anticipatory adaptation, and residual damage.[4]

Generic adaptive capacity captures the components not necessarily related to adaptation itself but to the economic development of a region. The underlining assumption is that the richer a region the more adaptable it is. Specific adaptive capacity depends not only on other forms of investment such as R&D and early warning systems, but also on institutional capacity. Both generic and specific adaptive capacity improve the effectiveness of adaptation measures.

As pointed out by Fankhasuer et al. (1998), the distinction between reactive and anticipatory adaptation is intuitively clear, but difficult to delineate in a dynamic setting. In the AD-WITCH model, reactive and anticipatory adaptations are defined as follows. Proactive or anticipatory adaptation is represented by the actions taken before the materialisation of the expected damage, reducing its severity once manifested. Typical examples of these activities are coastal protection, or infrastructure and settlements climate-proving measures. They need some anticipatory planning and if well designed, would be effective along the medium, long-term.

Reactive adaptation is represented by all those actions that need to be undertaken every period in response to those climate change damages that cannot be accommodated by anticipatory adaptation. They usually need to be constantly adjusted to changes in climatic conditions. Examples of these actions are energy expenditures for air conditioning or farmers' yearly changes in seasonal crops' mix.

The "adaptation basket," which exhibits decreasing marginal productivity, reduces the negative impacts of climate change on gross output. The "adaptation basket" is composed by the four different adaptation actions, which are modelled as a sequence of Constant Elasticity of Substitution (CES) nested functions (see Figure 2).

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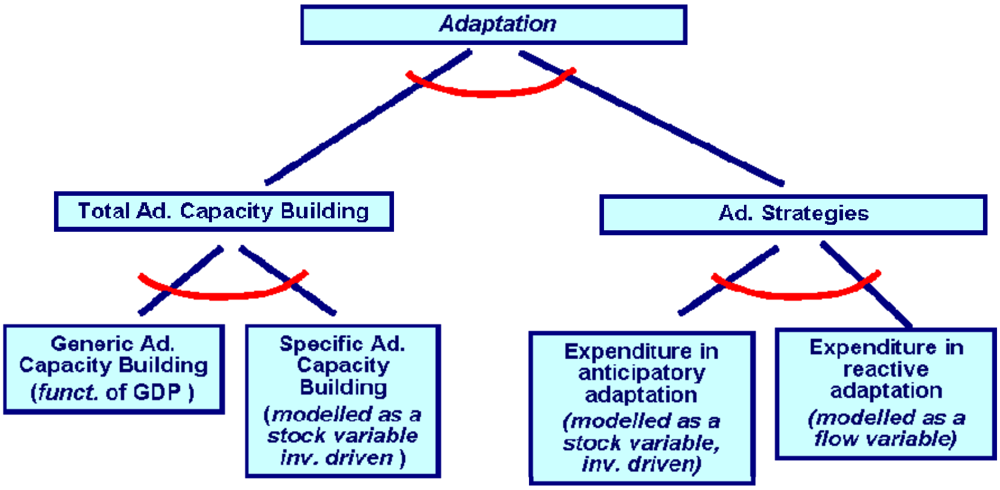
[4] In WITCH and AD-WITCH mitigation can be achieved by investing in set of mitigation options, namely energy efficiency innovation, low carbon power generation technologies and breakthrough technologies.

Figure 2: The adaptation tree in the AD_WITCH model



A first distinction is made between adaptive capacity building (left nest) and adaptation activities *strictu sensu* (adaptation strategies in the right nest).

Total adaptive capacity building is a combination of a generic and a specific component. Generic adaptive capacity building is represented as an exogenous trend increasing at the rate of total factor productivity. Specific adaptive capacity building is modelled as a stock. This accumulates over time with adaptation-specific investments.

Adaptation strategies include proactive and reactive measures. Proactive adaptation is modelled as a stock variable: defensive capital, accumulates over time because of a dedicated investments activity. As defensive capital does not disappear, investment is needed to contend with incremental climate change damage. Proactive adaptation is also subject to an economic inertia. An initial investment in adaptation takes five years[5] to accrue to the defensive stock, effectively reducing damage. Expenditure on reactive adaptation is modelled as a flow variable. In each simulation

[5] As usual in most IA models, including RICE, time *t* corresponds to either 5 or 10 years. In our model, one time period is equivalent to five years.

period, some expenditure is needed to confront climate change damages irrespectively to the expenditure in the previous period.

We model adaptation capacity building and adaptation activities as gross substitutes, similarly reactive and proactive adaptation. We set an elasticity of substitution equal to 1.2. General and specific adaptive capacity are modelled as gross complements with elasticity of substitution equal to 0.2[6].

The expenditure for each of the adaptation activities is then included into the national accounting identity. Investments in specific adaptive capacity, in proactive adaptation and reactive adaptation expenditure are three additional control variables decision makers are endowed with. They compete with other alternative uses of regional income in the maximisation of welfare, namely consumption, investments in physical capital, in different power generation technologies, and in energy R&D. More details on the theoretical setup can be found in Annex I.

Finally, adaptation as an aggregate (upper level in Figure 2) reduces the wedge between gross output, YG, and output net of climate damages, YN:

$$YN_{n,t} = \frac{1}{1 + CCDA_{n,t}} \cdot YG_{n,t}$$

The coefficient *CCDA* accounts for the total effect of climate change, including the effect of adaptation activities:

$$CCDA_{n,t} = f(ADAPT_{n,t}, CCD_{n,t}) = \frac{1}{1 + ADAPT_{n,t}} \cdot CCD'_{n,t}$$

where $CCD_{n,t} = \theta_{1n} \cdot T_t + \theta_{2n} T_t^{\gamma_n} + \theta_{3n}$ is a reduced form relationship between temperature and damages. This specification encompasses all the characteristics of previous modelling efforts and improves upon them. It includes the stock component of adaptation expenditure as emphasised in Bosello (2008), but not in de Bruin and Dellink (2009). Defensive capital can be built not only through investing in anticipatory adaptation strategies such as in Bosello (2008), but also building adaptive capacity. It captures the flow dimension of adaptation as done by de Bruin and Dellink

[6] In a sequence of sensitivity tests we verify the robustness of our results to many different assumptions on the degree of substitutability among adaptive options.

(2009), but only partially by Bosello (2008). Reactive adaptation is described as an expenditure flow confronting each period with residual damage, but without the possibility to affect damages that occur in the following period. This approach proposes a complete and flexible set-up to study the dynamics of adaptation. Stock and flow components can be contrasted comparing respective cost and benefits.

3.3 Calibration of AD-WITCH

The output losses induced by climate change in the WITCH model include both the cost of adaptation and residual damages. Calibrating adaptation in the AD-WITCH model implies to disentangle these two components. This requires implementing an adaptation function describing costs and benefits of the different forms of adaptation. A detailed description of the calibration process is reported in Annex II. Here, it is worth mentioning some points.

In principle the adaptation function in AD-WITCH should be parameterised to replicate the damage of the original WITCH model at the given calibration point (we choose years 2060 and 2065, when CO_2 concentration doubles). We have gathered more recent information on adaptation expenditure, summarised in Table 4. Our reference damages can differ from the WITCH ones because we have calibrated residual damage to be consistent with adaptation expenditure.

Table 6 demonstrates that quite large differences on climate change costs emerge between the literature results and the calibrated values for KOSAU, CAJAZ, TE, CHINA and LACA. According to the available literature (Nordhaus and Boyer 2000), the first four regions gain from climate change. However, the bottom-up literature on adaptation expenditure points out that they will spend between 0.14 and 0.68% of their GDP on adaptation. According to the optimising behaviour of the AD-WITCH model, if a region gains from climate change, it will not engage in positive adaptation expenditures. In these cases we “induced” adaptation expenditure by imposing positive damages in those regions. However, we also tried to keep residual damage in the range of reasonability. As a consequence, estimated and calibrated adaptation costs can diverge.

For LACA the problem is similar even though the literature reports damage from climate change. Total damages and protection levels are interdependent, thus it is not possible to lower LACA adaptation costs and bring them closer to their reference value without decreasing total damage further below the 2% of GDP. In other words, we always try to guarantee consistency between the three components of climate change costs.

It has to be pointed out that estimates on climate change damages and on adaptation costs are far from consolidated. For instance, Nordhaus in one of his recent papers (Nordhaus 2009) clearly states that he considers reliable only the global estimate of climate change and he does not differentiate anymore among regions. Parry et al. (2009) also stresses the large uncertainty of estimates. He underlines that in many sectors, especially coastal protection and infrastructure, residual damages are likely to be under-estimated. We therefore consider the assumption of positive damages in KOSAU, CAJAZ, TE and CHINA justifiable.

Table 3: Different adaptation strategies

Proactive Adaptation Activities → Modelled as “stock” variable
Coastal Protection Activities Settlements, Other Infrastructures (Excluding Water) and Ecosystem Protection Activities Water Supply (Agriculture and Other) Protection Activities
Reactive adaptation activities → Modelled as “flow” variable
Agricultural Adaptation Practices Treatment of Climate-Related Diseases Space Heating and Cooling Expenditure
Generic adaptive capacity → Modelled as an exogenous trend
In the present specification generic adaptive capacity building is represented by an exogenous trend increasing at the rate of total factor productivity
Investment in specific adaptive capacity → Modelled as a “stock” variable

Investments in specific capacity have been set to be the 1% of world expenditure on education and total R&D in the calibration year (in absolute terms this amounts to US$ 164 Billion in 2060). Then this global amount has been distributed across different regions proportionally to the normalised share of education expenditure over GDP

In our research however, we found information on three activities that can be considered investment in specific adaptive capacity: expenditure on early warning systems; research activities in the health sector, research activities for the development of climate-resilient crops. For completeness, we report them also in the Tables in Annex II.

Table 3 summarises the different adaptation activities for which data were available; Table 4 reports the costs of each of these activities as they emerged from the available literature and the values calibrated for the AD-WITCH model; Table 5 summarises estimated and calibrated protection levels; Table 6 introduces total damages proposed in Nordhaus and Boyer (2000), in the original WITCH model, those newly estimated by this study and the calibration results from the AD-WITCH model.

Table 4: Adaptation costs for a doubling of CO2 concentration in absolute values and as percentage of GDP.

Extrapolation from the literature and calibrated values with the AD-WITCH model

	Water in Agriculture (irrigation) (Billion $)	Water in Other Vulnerable Markets (Billion $)	Early Warning Systems (Million $)	Coastal Protection (Billion $)	Settl.mnts (Billion $)	Cooling Expenditure (Billion $)	Disease Treatment Costs (Billion $)	Adapt. R&D (Billion $)	TOTAL (Billion $)	TOTAL (% of GDP)	AD-WITCH (% of GDP)
USA	3.0	1.3	5	3.57	22.1	3.9	1.13	2.92	37.9	0.09	0.10
WEURO	4.7	2.0	5	5.03	56.2	-8.8	-0.68	2.44	60.9	0.18	0.27
EEURO	7.4	3.2	5	0.26	3.2	-0.8	-0.06	0.03	13.2	0.37	0.18
KOSAU	5.9	2.5	5	1.77	5.2	7.7	1.86	0.29	25.3	0.48	0.19
CAJAZ	1.6	0.7	5	2.87	9.8	-7.8	3.02	1.66	11.8	0.09	0.06
TE	10.1	4.3	5	1.66	3.2	0.6	0.13	0.06	20.1	0.28	0.15
MENA	50.7	21.7	5	1.24	3.9	18.6	2.12	0.14	98.5	1.06	0.81
SSA	13.4	5.7	5	2.68	3.9	10.4	0.51	0.01	36.6	0.70	0.62
SASIA	17.0	7.3	5	1.28	19.7	50.7	1.10	0.04	97.1	0.49	0.68
CHINA	3.0	1.3	5	1.26	17.2	45.5	0.29	0.16	68.6	0.20	0.11
EASIA	1.3	0.5	5	4.26	3.9	25.9	4.74	0.04	40.7	0.40	0.45
LACA	4.3	1.8	5	7.75	5.9	2.0	5.72	0.07	27.7	0.13	0.24

Table 5: Effectiveness of adaptation (1=100% damage reduction) for a doubling of CO2 concentration Extrapolation from the literature and calibrated values with the AD-WITCH model

	Agriculture	Other vulnerable markets	Cat. Events	Coastal systems	Settlements	Non market time use	Health	Weighted total (*)	AD-WITCH
USA	0.48	0.80	0.00	0.75	0.40	0.90	0.90	0.18	0.22
WEURO	0.43	0.80	0.00	0.54	0.40	0.80	0.90	0.13	0.13
EEURO	0.43	0.80	0.00	0.63	0.40	0.80	0.60	0.30	0.27
KOSAU	0.27	0.80	0.00	0.62	0.40	0.80	0.81	0.16	0.18
CAJAZ	0.38	0.80	0.00	0.37	0.40	0.90	0.69	0.20	0.11
TE	0.38	0.80	0.00	0.37	0.40	0.80	0.70	0.12	0.12
MENA	0.33	0.40	0.00	0.55	0.40	0.63	0.60	0.34	0.46
SSA	0.23	0.40	0.00	0.30	0.40	0.30	0.20	0.21	0.19
SASIA	0.33	0.40	0.00	0.47	0.40	0.50	0.35	0.19	0.23
CHINA	0.33	0.40	0.00	0.76	0.40	0.70	0.40	0.15	0.21
EASIA	0.33	0.40	0.00	0.25	0.40	0.43	0.40	0.18	0.21
LACA	0.38	0.40	0.00	0.46	0.40	0.70	0.90	0.38	0.25

(*) Reduction in each category of damage is weighted by the % contribution of that damage type to total damage. Then weighted damages are summed.

Table 6: Total climate change costs (residual damages and adaptation cost) for a doubling of CO2 concentration as a percentage of GDP

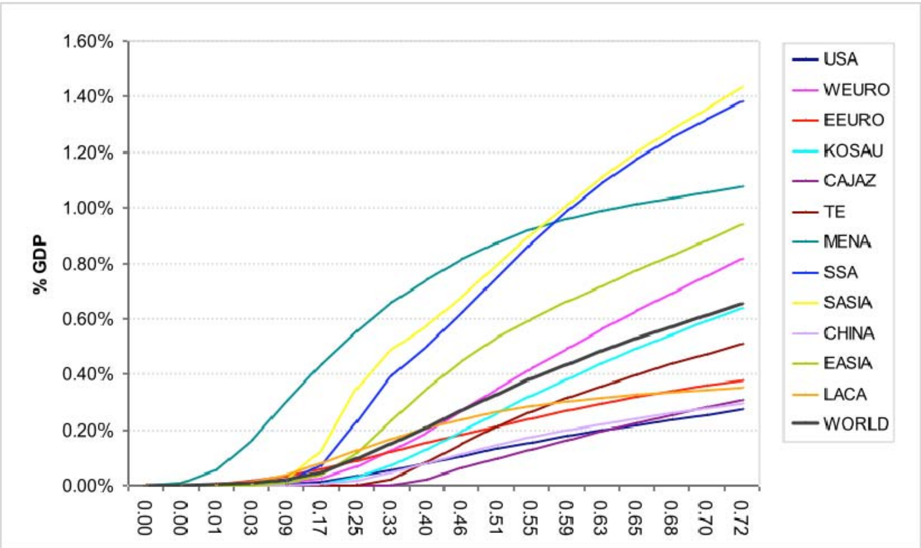
	Nordhaus and Boyer (2000)	WITCH model	This study survey of the literature	AD-WITCH model
USA	0.45	0.41	0.4	0.5
WEURO	2.84	2.79	2.2	1.9
EEURO	0.70	-0.34	0.8	0.9
KOSAU	-0.39	0.12	0.2	1.0
CAJAZ	0.51	0.12	0.01	0.2
TE	-0.66	-0.34	-0.01	0.7
MENA	1.95	1.78	2.5	2.8
SSA	3.90	4.17	4.2	4.2
SASIA	4.93	4.17	4.8	4.4
CHINA	0.23	0.22	0.2	0. 6
EASIA	1.81	2.16	1.8	2.2
LACA	2.43	2.16	2.1	1.2

Figures 3 and 4 introduce the adaptation cost curves produced by the AD-WITCH model. They depict the relationship between the effectiveness of adaptation, measured as reduced damage, and the costs of achieving that reduction. As recently pointed out by Parry et al. (2009), adaptation costs are likely to vary largely across regions, but in most cases reduction of the first 10% of damage will be much cheaper than the remaining 90%. Adaptation costs are indeed convex. They tend to be higher in developing than in developed regions[7].

The higher the damage, the higher the expenditure needed to reduce that damage. Non-OECD countries experience higher climate change damages than OECD countries in percentage of their GDP and often in absolute terms. This explains why they have to bear higher adaptation costs.

However, this is only part of the story. China for instance, faces lower damages than TE (Table 6), but shows nonetheless higher adaptation costs. This is because the source of the damage is also relevant. The largest "damage component" in TE are catastrophic events which are generally "unadaptable." If one excludes the operation of "cheap" early warning systems that can save lives but only partially protect physical capital, catastrophic events do not induce large adaptation expenditure. This illustrates why protection costs in TE are low, despite high damages.

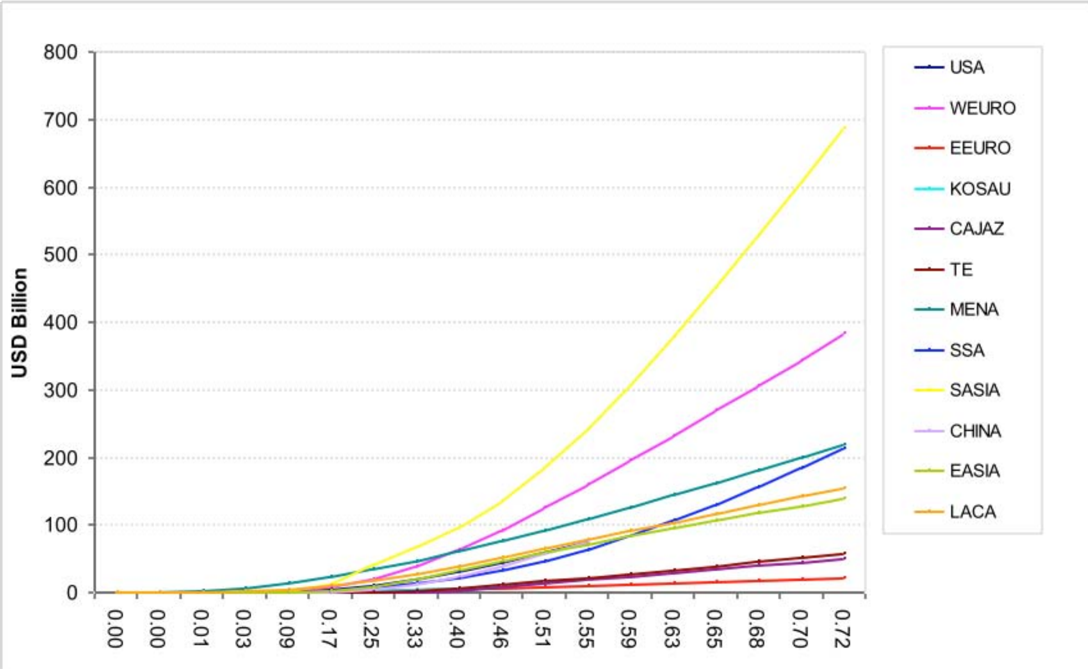
Figure 3: Adaptation Cost Curves in the AD-WITCH model - Percentage of Current Gross Domestic Product (*)



(*) Each point in the curves corresponds to a different year

[7] The convexity is more evident when costs are expressed in levels (US$ Billion). When measured as a percentage of GDP, adaptation curves are still convex in developed regions. When GDP grows faster than adaptation expenditure, adaptation curves become convex. This occurs mostly in developing countries and in the second part of the century.

Figure 4: Adaptation Cost Curves in the AD-WITCH model - US$ Billion



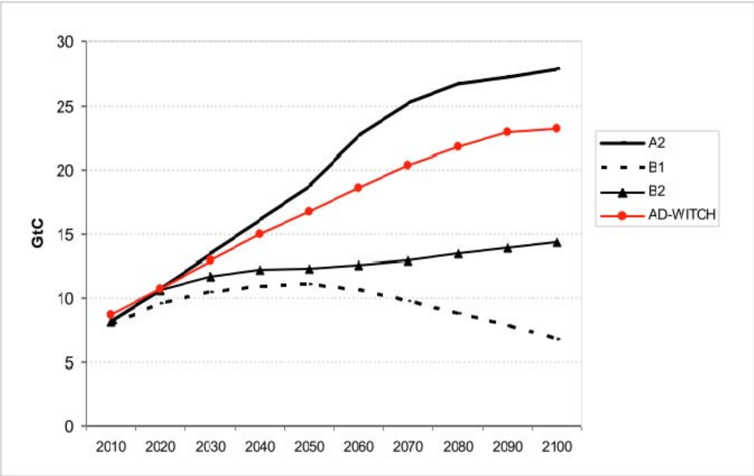
4. Policy simulations with AD-WITCH

This section will first provide a summary of the Business as Usual scenario of the AD-WITCH model in comparison with three IPCC SRES scenarios. Section 4.2 investigates how the different components of climate change costs vary across different policy scenarios. More precisely, the intertemporal dynamics and the regional heterogeneities of each component of climate change costs will be illustrated. Section 4.3 compares AD-WITCH with previous adaptation modeling attempts, namely AD-DICE, AD-RICE and AD-FEEM-RICE.

4.1 Baseline Scenario Comparison

Baseline emissions, temperature and world GDP from the AD-WITCH model are compared with major IPCC SRES (IIASA)[8] in Figures 5, 6 and 7 respectively. Figure 5 depicts the emission path for each scenario. AD-WITCH falls within the A2 and B2 scenarios and is characterised by an emission path that reaches 23 GtC by the end of the century. It follows closely the A2 until 2030, but afterwards AD-WITCH CO2 emissions grow at a lower rate.

Figure 5: CO2 emissions estimates of the IPCC SRES (IIASA) and the AD-WITCH baseline scenario.



As expected, the scenario hierarchy of emissions is also reproduced with temperature increase above pre-industrial level, as seen in Figure 6. However, the gap between scenarios is smaller than in the case of emissions, reflecting different assumptions on climate sensitivity.

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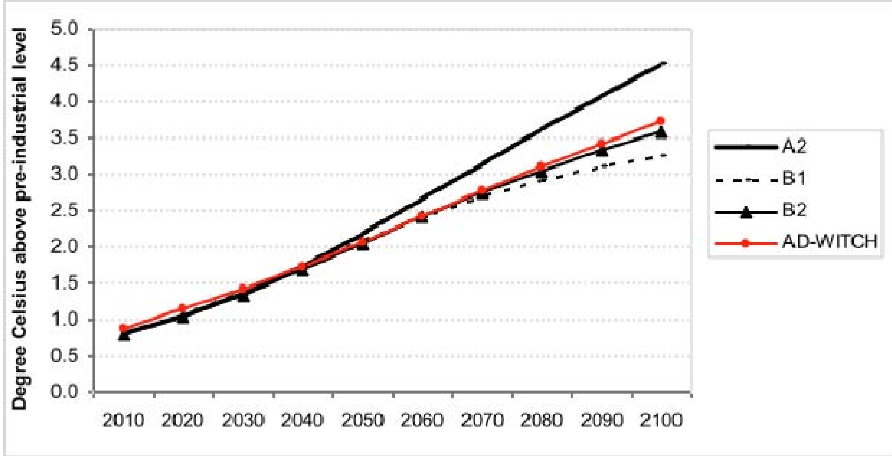
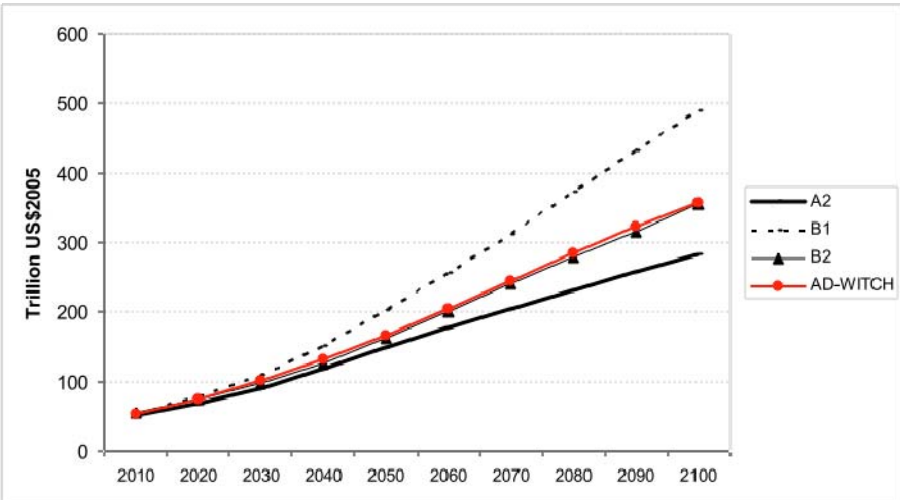
8 Available at: http://www.iiasa.ac.at/Research/GGI/DB/

Figure 6: Temperature estimates of the IPCC SRES (IIASA) and the AD-WITCH baseline scenario



In terms of Gross World Product (GWP), AD-WITCH closely replicates the B2 scenario.

Figure 7: Gross World Product estimates of the IPCC SRES (IIASA) and the AD-WITCH baseline scenario



4.2 Assessing the role of adaptation

Four scenarios will be discussed in the remaining of this section. The Baseline Scenario (BaU) will be compared with a scenario that allows for optimal adaptation (ADAPTATION). Two stabilisation scenarios are considered, the first entailing mitigation only (MITIGATION) and the second one including optimal adaptation (MITIGATION+ADAPTATION). Box 1 summarises the four scenarios considered.

Box 1. Baseline and Policy scenarios

BaU: Baseline (no adaptation, no mitigation).

ADAPTATION: Scenario with optimal adaptation.

MITIGATION: Stabilisation scenario without adaptation. The target is to stabilise concentrations at 550 CO2-eq or equivalently radiative forcing at 3.7 W/m^2. The policy target is reached cost effectively through a global emission trading scheme. Permits are allocated on equal emission per capita basis.

MITIGATION+ADAPTATION: Same as mitigation, including optimal adaptation.

In the mitigation and the mitigation+adaptation scenarios, the mitigation effort is given. We consider a policy that stabilises GHGs concentrations at 550 ppm CO2-eq. Given the mitigation target, we compute the optimal investments strategies in different energy technologies, physical investments, R&D expenditure and adaptation. These investments are a consequence of the mitigation target and they identify the optimal policy mix to achieve a given mitigation target. The mitigation+adaptation scenario makes it possible to investigate the potential role of adaptation in the presence of a specific mitigation policy. This approach is consistent with the large majority of climate change policy studies, but it adds a new dimension to the optimal policy mix to achieve the 550 ppm target, namely adaptation.

In the WITCH model, and in AD-WITCH, mitigation is not a single choice variable as it is the case in the DICE model. It is rather the result of a series of investment decisions in mitigation options. The abatement and mitigation decisions are taken non-cooperatively. Each regional planner responds to domestic damages, without internalising the global environmental externality she imposes on other regions. This leads to a noncooperative equilibrium. The noncooperative equilibrium of the AD-WITCH model mimics the regional incentive to free ride on other regions' emission reductions. As a consequence, abatement levels are much lower than the social optimum and they are close to zero.

4.2.1 Adaptation versus Baseline Scenario

Emissions

The possibility to adapt offers an additional option to control the negative impacts of climate change. Damages from GHG emissions are smaller, and thus the need to curb emissions trough a cleaner mix of energy production technologies, R&D and physical investments is lower. Accordingly, emissions increase from the +0.1% in Easter Europe to +6.2% in and South Asia in the second half of the century (Figure 8).

The effect is particularly pronounced in those regions characterised by high damages and therefore by higher adaptation effort namely, South Asia, Middle East-North Africa and Sub-Saharan Africa (see also Table 4). Most of the increase takes place in the second half of the century. Figure 9 shows the relationship between adaptation-induced emission increases and total adaptation costs. For expenditure levels above 0.6% of GDP, emissions tend to increase with adaptation.

Figure 8: Impact of adaptation on energy carbon emissions

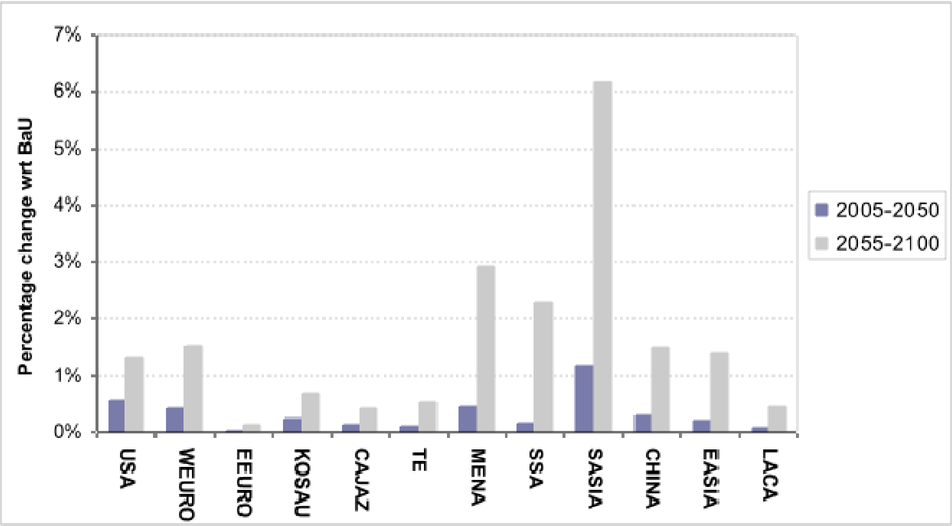
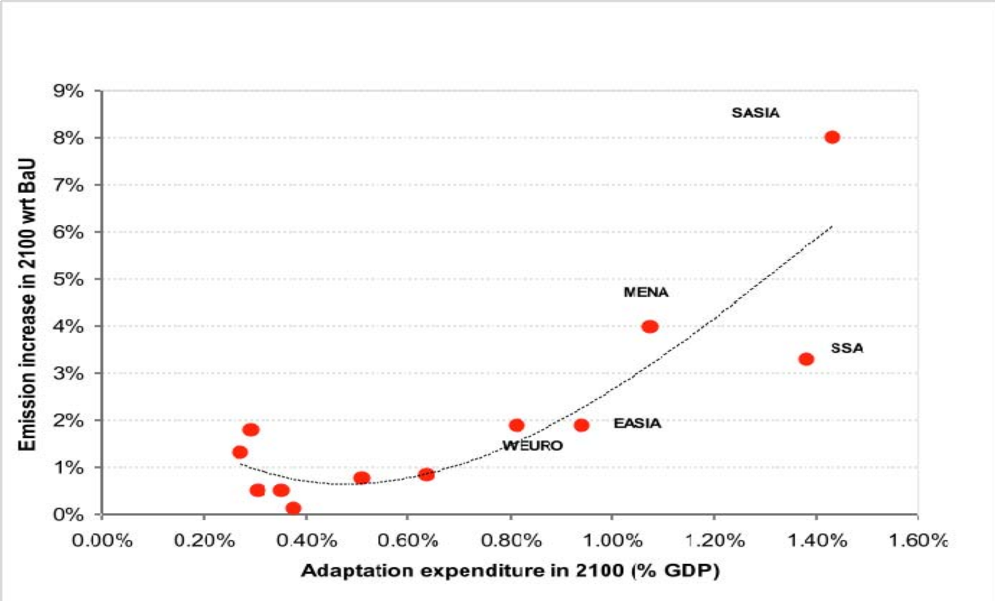


Figure 9: Explaining the impact of adaptation on CO2 emissions

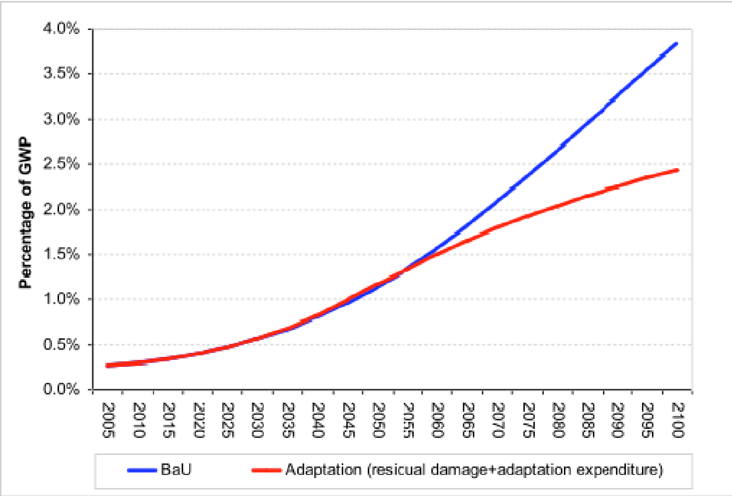


Climate change costs

Notwithstanding higher emissions, adaptation reduces substantially the damage inflicted by climate change on economic systems. As shown by Figure 10 (left panel) climate change costs, inclusive of adaptation expenditure, are lower in the ADAPTATION scenario than in the BaU scenario. In 2100, for the world as a whole, adaptation roughly halves damages from US$13 to 6 Trillion (Table 7). In some regions, adaptation would begin in 2015, but its effects are really appreciable after 2040 when climate change damage would be sufficiently high.

Figure 10 (right panel) disentangles the components of climate change cost for the world and Table 7 adds information on the OECD and the non-OECD regions. Residual damages represent the bulk of climate change costs both for OECD and non-OECD countries all over the century. For the world as a whole, their share is declining from 99% in 2030 to 73% in 2100, but in that year they still erode almost 2% of world GDP. This holds despite the presence of optimal adaptation which in 2100 builds the remaining 27% of costs and it stresses the need for additional policies to curb damages.

Figure 10: Composition of climate change costs



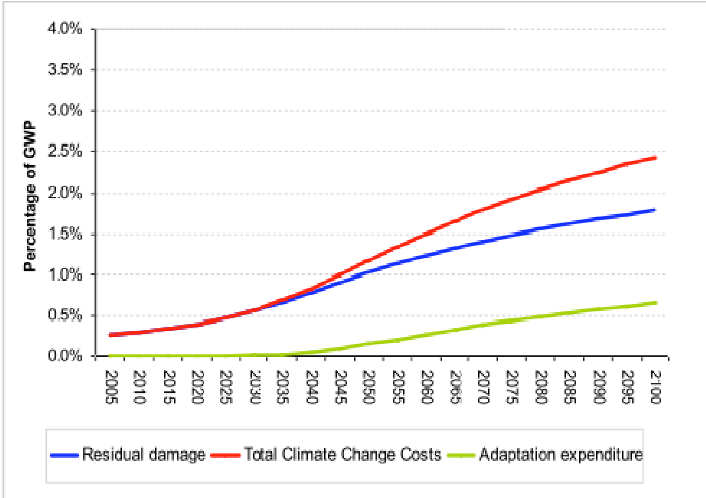


Table 7 shows that most adaptation is undertaken by non-OECD countries whose expenditure in 2100 more than doubles that of OECD regions. This result is driven by the time and spatial distribution of climate change impacts, which hit earlier and more severely developing countries. Adaptation effort is particularly large in the more vulnerable regions, namely SSA, SASIA, MENA.

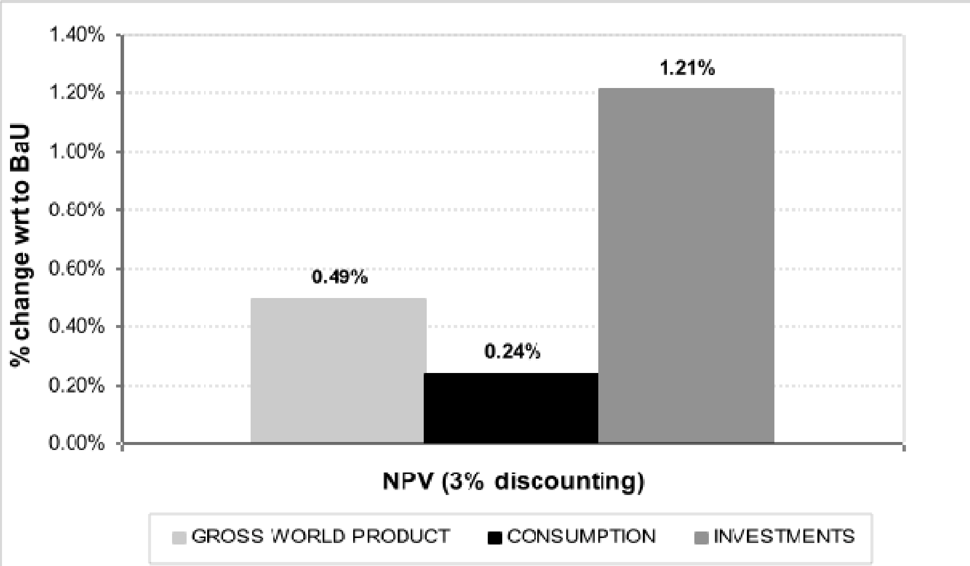
Table 7: Building-up of climate costs in the baseline with adaptation scenario (ADAPTATION) in 2030, 2050, 2100

Annual Average Costs (2005 US$ Billion)			
2030	WORLD	OECD	NON_OECD
Total Adaptation Expenditure	8.4	1.2	7.2
Residual damage	562	241	322
Reduced Damage	2	0.2	1.7
Total Costs	571	242	329
2050	WORLD	OECD	NON_OECD
Total Adaptation Expenditure	250	64	187
Residual damage	1705	593	1112
Reduced Damage	194	35	159
Total Costs	1955	657	1299
2100	WORLD	OECD	NON_OECD
Total Adaptation Expenditure	2331	677	1654
Residual damage	6376	1783	4593
Reduced Damage	7035	1574	5461
Total Costs	8707	2460	6247

Welfare

Not surprisingly adaptation improves welfare. By controlling the damages related to GHG emissions, adaptation allows for a higher economic growth. Compared to the BaU case (see Figure 11), higher emissions can be tolerated and thus also higher (total discounted) investments (+1.21%), output (+0.49%) and consumption (+0.24%).

Figure 11: Impact of adaptation on macroeconomic indicators



As depicted by Table 8, the consumption effect is however a typical long-term one. During the first half of the century, increased adaptation expenditure crowds out consumption, which in the ADAPTATION scenario is lower than in the BaU. Eventually consumption levels fostered by enhanced investments increase compared to BaU.

Table 8: Impact of adaptation on macroeconomic indicators in 2030, 2050, 2100. Percentage difference compared to BaU

	GROSS WORLD PRODUCT	CONSUMPTION	INVESTMENTS
2030	0.01%	-0.02%	0.13%
2050	0.17%	-0.05%	0.94%
2100	2.62%	1.77%	4.84%

The Optimal Adaptation Mix

The AD-WITCH model distinguishes between expenditure on adaptation measures *strictu sensu* and adaptive capacity-building. One of the first policy decisions is whether to allocate money to enhance local adaptive capacity or to specific adaptation plans.

AD-WITCH considers two different forms of capacity. Generic capacity, which grows exogenously at the growth rate of total factor productivity. The specific one which instead depends on endogenous dedicated investment. As shown in Figure 12, generic capacity grows faster in non-OECD countries, reflecting the convergence hypothesis behind the growth process in the AD-WITCH model. Expenditure for building up specific adaptive capacity is larger in developing regions, which begin with a lower capacity level (see Annex II, Table AII.10). This also depends on their higher adaptation needs and on the pull effect of generic capacity as the two are modelled as complements.

Figure 12: Generic and specific adaptive capacity: world and regional patterns

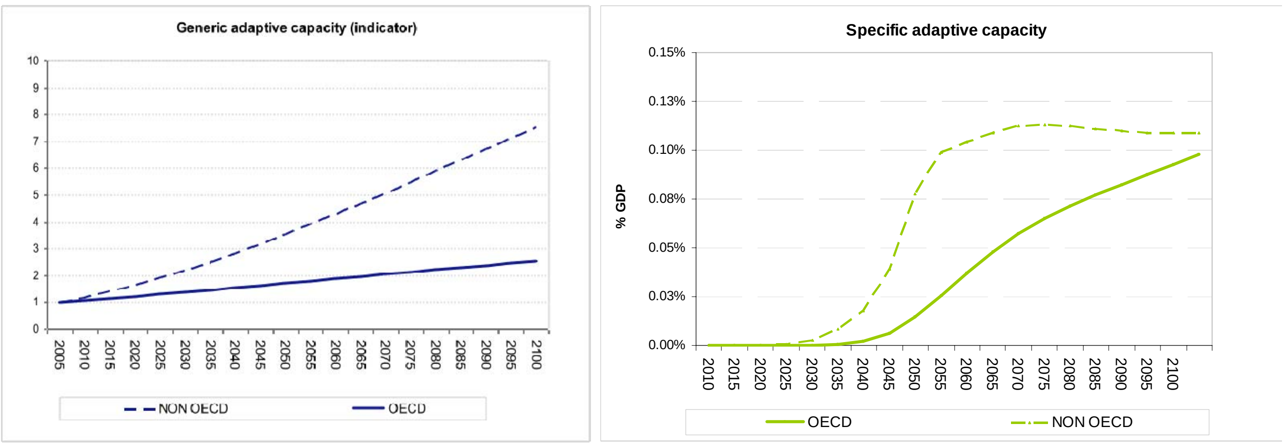
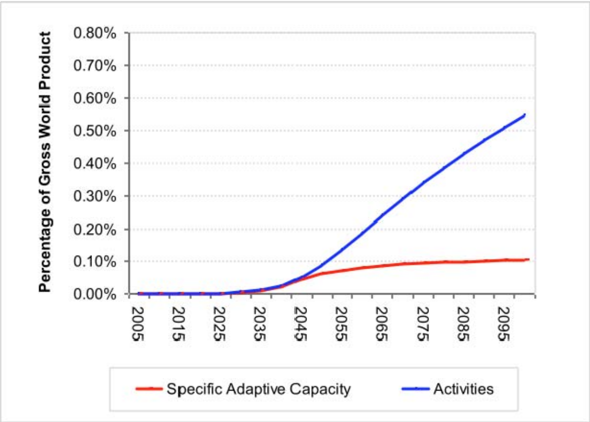
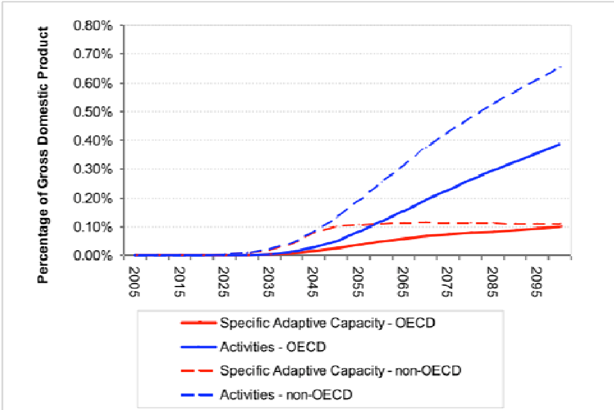


Figure 13 singles out the optimal allocation of resources between adaptation activities and adaptive capacity building. Specific capacity absorbs only a small fraction of the resources devoted to adaptation (see also Table 9). Its share over total adaptation expenditure decreases over time from 44% in 2030 to 16% in 2100. Specific capacity needs to be built initially to exploit better adaptation activities. Once constituted, it leaves room to adaptation. Compared to OECD, non-OECD countries allocate more resources on capacity building, especially in the first half of the century. This reflects their adaptation deficit and their greater exposure to climate damages which is a constant of all the exercise and concerns all adaptation forms.

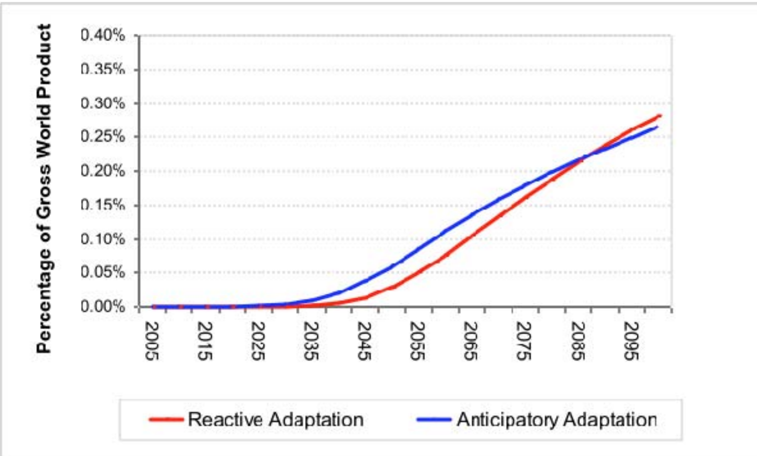
Figure 13: Activities and capacity: world and regional optimal mix





Turning to different adaptation activities shown in Figure 14, anticipatory adaptation starts immediately while reactive adaptation five years after. They both increase as a percentage of GDP. Anticipatory adaptation absorbs the larger amount of resources until 2085 then it is surpassed by reactive adaptation.

Figure 14: Adaptation strategy mix (cost of adaptation) - WORLD



Proactive adaptation is anticipated as it builds a stock of defensive capital that must be ready when the damage materializes, but faces an economic inertia. On the contrary, reactive adaptation is immediately effective and it can be used when the damage effectively materializes. This also explains why more resources are placed on reactive adaptation in the last decade. Damage grows too much and too fast to be accommodated prevalently with anticipatory measures.

Figure 15 and Table 9 highlight interesting differences between developed (OECD) and developing (non-OECD) countries. In the ADAPTATION scenario, the dominating form of adaptation in OECD regions is always anticipatory adaptation, while reactive adaptation becomes prominent in the long-run in non-OECD. This behaviour is driven by two facts. First, the regional composition of climate change vulnerability. In OECD countries, the higher share of climate change damages originates from infrastructures and coastal areas. Their protection requires a form of adaptation that is largely anticipatory (of the stock type). In non-OECD countries a higher share of damages originates from agriculture, health, and energy sectors (space heating and cooling). These types of damages can be accommodated more effectively with reactive measures (of the flow type). Second, OECD countries are richer. They can then easily give up their present consumption to foster anticipatory adaptation which is similar in nature to an investment as it will become productive in the future. On the contrary, non-OECD countries are compelled by resource scarcity to act in emergency.

Figure 15: Composition of adaptation costs – OECD and non-OECD

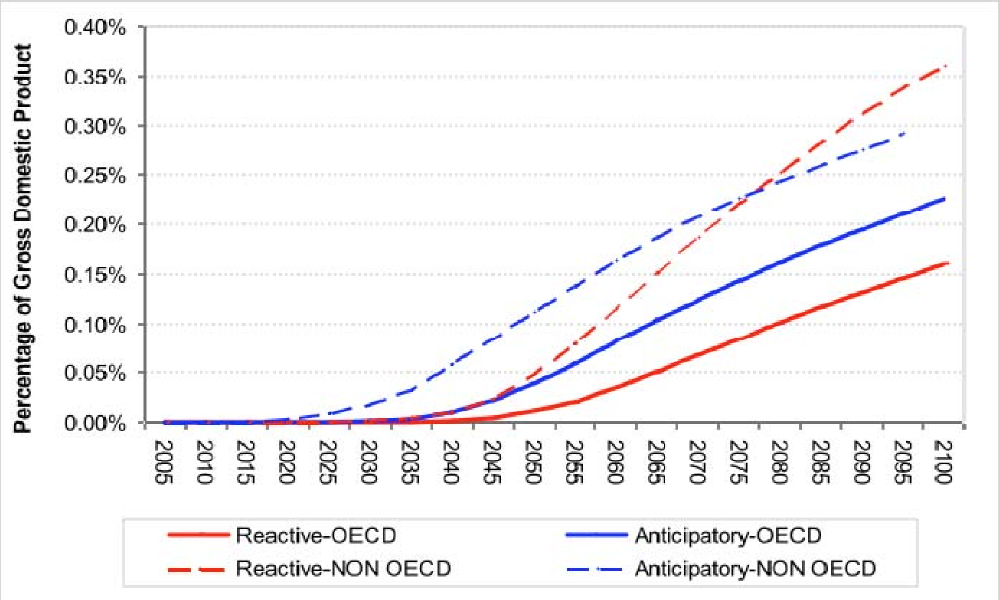


Table 9: Building-up of climate costs in the ADAPTATION scenario in 2030, 2050, 2100

Annual Average Costs (2005 US$ Billion)			
2030	WORLD	OECD	NON_OECD
Reactive Adaptation	0.6	0.1	0.5
Anticipatory Adaptation	4.0	0.7	3.3
Specific Adaptive Capacity Building	3.7	0.4	3.3
Total adaptation expenditure	8.4	1.2	7.2
2050	WORLD	OECD	NON_OECD
Reactive Adaptation	48	9	38
Anticipatory Adaptation	101	33	68
Specific Adaptive Capacity Building	102	22	80
Total adaptation expenditure	250	64	187
2100	WORLD	OECD	NON_OECD
Reactive Adaptation	1007	223	784
Anticipatory Adaptation	950	317	634
Specific Adaptive Capacity Building	374	137	237
Total adaptation expenditure	2331	677	1654
Shares (Percentage over total adaptation expenditure)			
2030	WORLD	OECD	NON_OECD
Reactive Adaptation	7%	8%	7%
Anticipatory Adaptation	48%	56%	47%
Specific Adaptive Capacity Building	44%	36%	46%
2050	WORLD	OECD	NON_OECD
Reactive Adaptation	19%	15%	21%
Anticipatory Adaptation	40%	51%	36%
Specific Adaptive Capacity Building	41%	34%	43%
2100	WORLD	OECD	NON_OECD
Reactive Adaptation	43%	33%	47%
Anticipatory Adaptation	41%	47%	38%
Specific Adaptive Capacity Building	16%	20%	14%

Table 10 summarises adaptation expenditure and climate change damages in Net Present Values using a 3% discount rate. Total climate change damages are higher in Sub-Saharan Africa (SSA) and South Asia (SASIA), when expressed as a percentage of GDP. However, in absolute values adaptation expenditure especially in SSA is very low compared to SASIA or to some developed countries such as Western Europe.

Table 10: Regional components of damage and adaptation costs from 2005 to 2100 in Net Present Values (3% discounting, 2005 US$ Billion except GDP in Trillion)

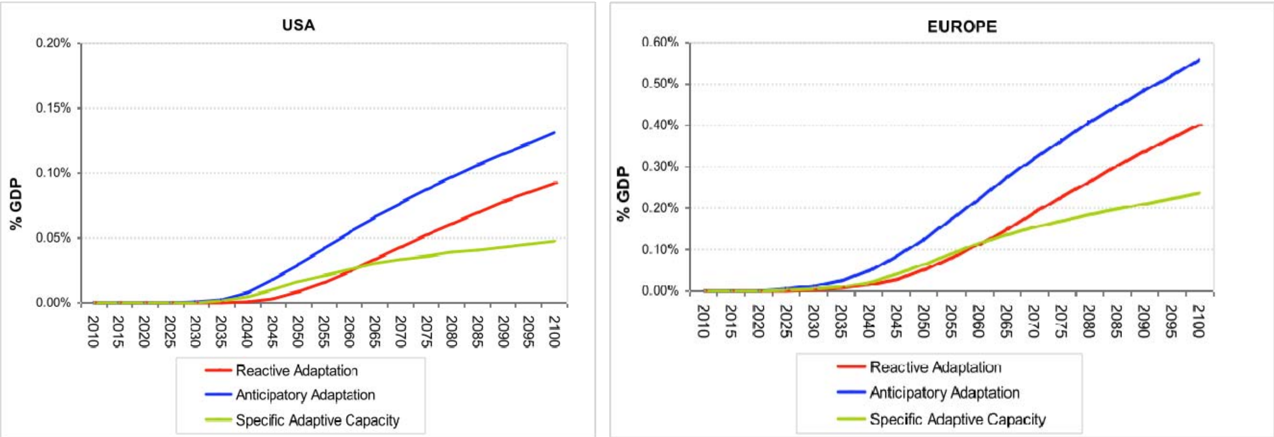
	Total damage	Total adaptation expenditure	Expenditure on reactive adaptation	Investments in anticipatory adaptation	Investments in specific adaptative capacity	Residual damage	GDP	Total damage as a percentage of GDP (%)
USA	3079	563	158	283	122	2516	884	0.3%
WEURO	10362	1216	308	555	353	9146	801	1.3%
EEURO	519	83	28	45	10	436	70	0.7%
KOSAU	739	145	44	79	23	594	117	0.6%
CAJAZ	220	128	36	70	22	92	323	0.1%
TE	540	154	5	124	25	386	134	0.4%
MENA	3707	941	278	414	249	2766	162	2.3%
SSA	3230	537	239	236	61	2693	85	3.8%
SASIA	12075	1987	821	803	363	10088	298	4.1%
CHINA	2691	550	304	63	183	2142	535	0.5%
EASIA	2804	512	175	188	148	2292	163	1.7%
LACA	3908	611	204	192	215	3297	361	1.1%
GLOBAL	43874	7424	2600	3051	1774	36450	3932	1.1%
OECD	14919	2134	573	1032	529	12785	2194	0.68%
NON OECD	28955	5290	2026	2019	1245	23665	1737	1.67%

An important issue concerns the effective availability of resources to meet the adaptation needs highlighted by the present exercise. In 2050, developing countries are expected to spend almost US$ 200 Billion to adapt to climate change, roughly twice the present total ODA flow (US$ 100 Billion). This expenditure would then increase exponentially. On a annuitised base non-OECD would need about US$ 500 Billion (or 0.48% of their GDP) for adaptation against the US$ 200 Billion (or 0.22% of GDP) of OECD. It is quite unlikely that developing countries would have the resources to meet their adaptation needs. This would call for international aid and cooperation on adaptation. As an exercise, we computed on an annuitised base, the transfer[9] that would equalise adaptation expenditure over GDP between OECD and non-OECD countries. It corresponds to US$ 270 Billion (from OECD to non-OECD). This means that OECD group would finance roughly 54% of adaptation in non-OECD with a cost equalling 0.3% of their GDP.

Figure 16 and 17 show the breakdown of adaptation expenditure in selected OECD and non-OECD regions. Developing countries allocate the initial effort to improve their specific adaptive capacity. Expenditure on activities becomes more prominent only after mid century. South Asia and Sub-Saharan Africa, together with East Asia, are the regions with the lowest initial level of general capacity. Eliminating the adaptation deficit is a priority in these regions. This explains the sharp initial increase in specific capacity investments. Once a minimum capacity level has been built, resources would be redirected towards adaptation activities.

OECD regions instead do not need to further develop adaptive capacity and devote most resources to adaptation activities. The comparison of USA and EU highlights the large heterogeneities of climate change distribution even within industrialized countries.

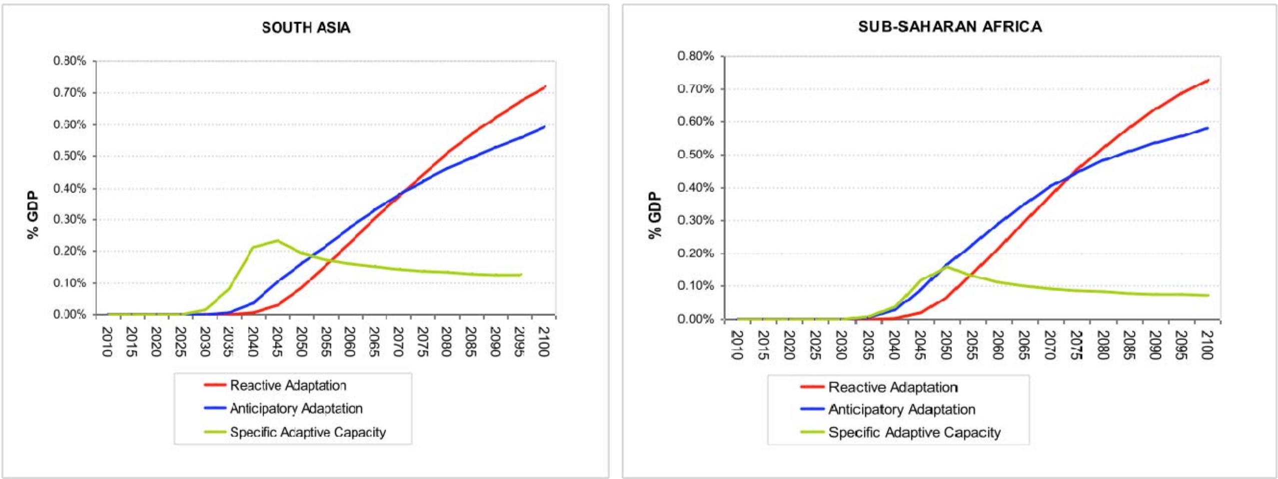
Figure 16 : Adaptation expenditure in selected OECD regions



[9] The formula that has been used to compute the transfer is the following:

$$\frac{ADA\exp\_OECD}{GDP\_OECD - T} = \frac{ADA\exp\_NONOECD - T}{GDP\_NONOECD}$$

Figure 17: Adaptation expenditure in selected non-OECD regions



Summing up, the ADAPTATION scenario is characterized by the following features:

1. *Composition*

The optimal mix of adaptation strategies consists of reactive, anticipatory measures, and investments in specific adaptive capacity. All three adaptation forms are used with a different timing.

2. *Timing*

Proactive adaptation occurs earlier and is the main adaptation mode until 2085. Reactive measures prevail afterwards, when the damage is higher.

3. *Regional patterns*

Non-OECD countries sustain a higher adaptation expenditure than OECD countries as a percentage of their GDP, but also in absolute terms. They are exposed to higher and earlier damages. OECD countries spend a higher fraction of their GDP on anticipatory adaptation than non-OECD countries, which allocate more resources to reactive adaptation.

4. *Capacity building*

Adaptive capacity (generic and specific) is initially larger in OECD regions. As a consequence, adaptation is immediately effective in those regions. Non-OECD regions need to build up a capacity stock especially in the first half of the century. They invest a larger share of resources on specific capacity. Capacity is an essential prerequisite for successful adaptation activities and must be developed before climate damages become sizable.

5. Distributional implications

The ADAPTATION scenario clearly highlights the higher exposure to climate change and the adaptation gap of the developing world. It predicts a much higher adaptation need in those regions. The indicative size of the required investment and its uneven distribution stress the need for international cooperation on adaptation.

4.2.2 Mitigation and Adaptation Equilibrium Strategies

This section provides quantitative and qualitative insights on the interdependency between mitigation and adaptation. It discusses the effect of mitigation on the optimal adaptation patterns. In particular, it considers a mitigation policy aimed at stabilising CO2-eq concentrations at 550 ppm (or equivalently radiative forcing at 3.7 W/m^2).[10]

As shown by Figure 18, an ambitious stabilisation policy can increase damage reduction significantly. While optimal adaptation alone can reduce climate damages up to US$ 7 Trillion in 2100, mitigation and adaptation together can achieve about US$ 10 Trillion.

Table 11 and Figure 19 explain what happens within this new policy mix. Table 11 breaks down the components of climate change costs into mitigation, adaptation, and residual damage in 2030, 2050 and 2100. Mitigation expenditure starts earlier because it has to go through the inertia of the carbon cycle. On the contrary, adaptation directly impacts climate change damage. Therefore it can be postponed until damage becomes really high. The ratio between mitigation and adaptation is decreasing because more abatement effort is required during the first half of the century. However, compared with adaptation, mitigation expenditure prevails all over the century.

Mitigation effort is slightly larger in the presence of adaptation because of the positive impact of adaptation on emissions (see Figure 8). Mitigation lowers the need to adapt and crowds out

[10] A stabilisation policy is simulated by defining a global path of GHG emissions consistent with a given stabilisation target, in this exercise 550 CO2-eq, which determines the global cap on emissions. Emission permits have been allocated on an equal per capita basis so as to equalise the entitlement to pollute across regions. Regions can then buy and sell permits on the global market so as to achieve the target in the most cost-effective way, equalising marginal costs of abatement.

adaptation expenditures. In the short-run, total costs are slightly higher in the presence of adaptation, but mitigation and adaptation expenditure are compensated by a much lower residual damage in the long-run.

Figure 19 shows that mitigation is the prevailing climate change strategy also in terms of damage reduction. The proposed CO2 stabilisation policy halves climate change damages, leaving a residual damage equal to 2% of gross world product. Adaptation reduces the unadapted damages to about one additional fourth.

Figure 18: Effect of mitigation and adaptation on residual damage

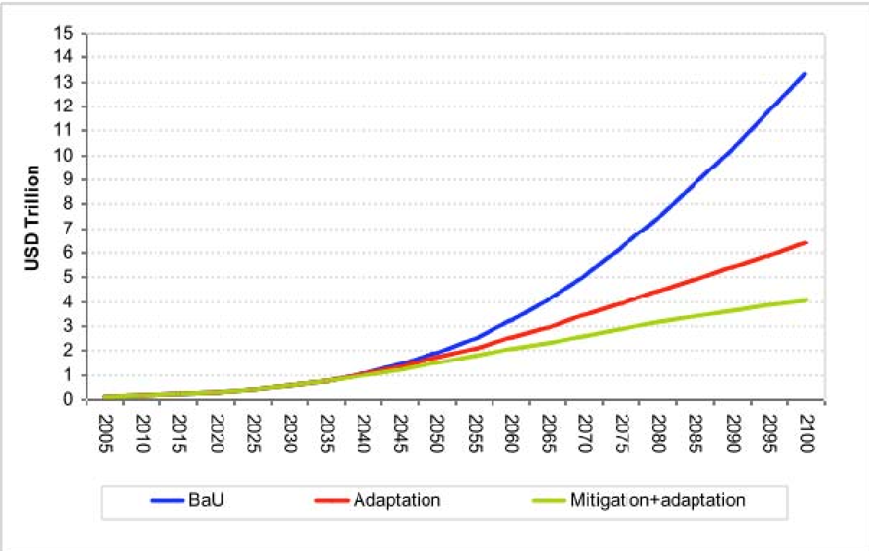
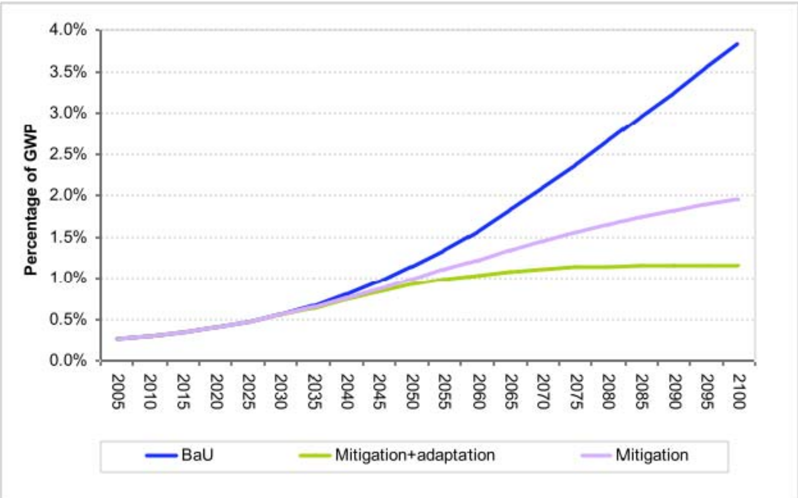


Table 11: Building-up of climate costs in the mitigation scenario with and without adaptation in 2030, 2050, 2100

Annual Average Costs (2005 US$ Billion)			
2030	Adaptation	Mitigation	Mitigation+adaptation
Mitigation expenditure	0	764	817
Adaptation expenditure	8	0	6
Residual damage	562	550	548
Total Costs	571	1314	1371
2050	Adaptation	Mitigation	Mitigation+adaptation
Mitigation expenditure	0	1041	1073
Adaptation expenditure	250	0	136
Residual damage	1705	1601	1494
Total Costs	1955	2642	2704
2100	Adaptation	Mitigation	Mitigation+adaptation
Mitigation expenditure	0	1531	1548
Adaptation expenditure	2331	0	1021
Residual damage	6376	6775	4065
Total Costs	8707	8306	6634

Figure 19: Contribution of adaptation and mitigation to residual damage reduction



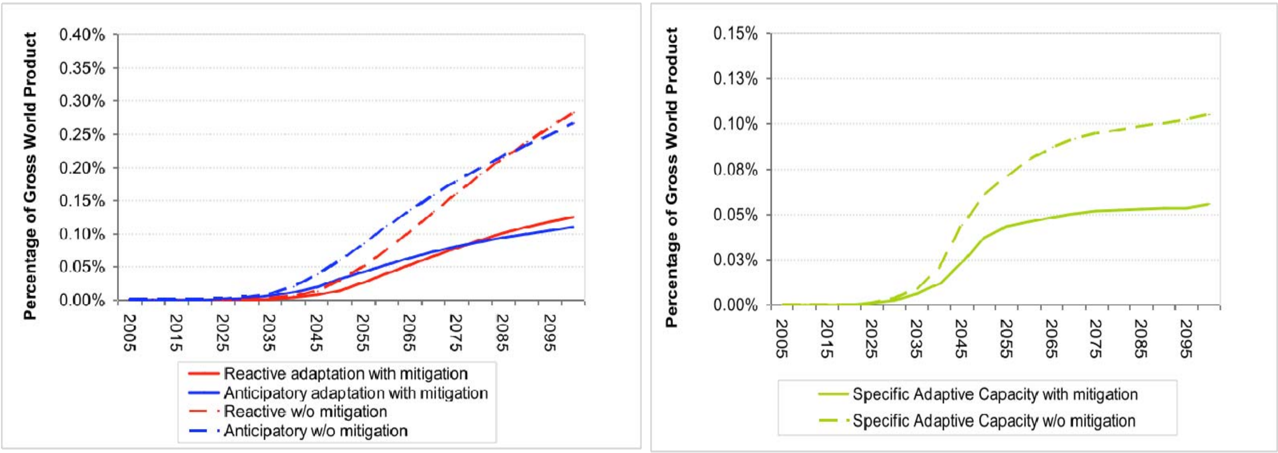
Mitigation lowers the need to adapt and crowds out adaptation expenditures. Table 12 shows an equal reduction in all adaptation expenditures of about 55%, with a slightly larger reduction in OECD regions (overall -66%).. Mitigation reduces the damage, but without changing its qualitative nature (see Figure 19). Therefore, it can be seen as a sort of scaling factor for adaptation. Albeit small, mitigation induces an adjustment in the adaptation mix in favor of reactive adaptation and investment in specific adaptation. Anticipatory adaptation is the adaptation option more similar to mitigation and it is thus the one suffering the strongest crowding out.

Table 12: Composition of adaptation expenditure with and without mitigation (2005 US$ Billion, NPV 3% discounting)

Adaptation	WORLD	OECD	non-OECD
Reactive Adaptation	2600	573	2026
Anticipatory Adaptation	3051	1032	2019
Specific Adaptive Capacity Building	1774	529	1245
Mitigation + adaptation	WORLD	OECD	non-OECD
Reactive Adaptation	1220	198	1022
Anticipatory Adaptation	1362	349	1013
Specific Adaptive Capacity Building	962	179	783
Percentage change	WORLD	OECD	non-OECD
Reactive Adaptation	-53%	-66%	-50%
Anticipatory Adaptation	-55%	-66%	-50%
Specific Adaptive Capacity Building	-46%	-66%	-37%

Consequently, as shown in Figure 20, the time and composition profile of adaptation remain unchanged. The optimal mix entails more anticipatory measures in early years, whereas reactive adaptation becomes more effective later on. Mitigation anticipates the crossing point between the two adaptation activities of about 10 years.

Figure 20: Composition of adaptation activities and investments in specific adaptive capacity with and without mitigation over time



Lower expenditure on adaptation implies a lower contribution of adaptation to damage reduction. However, adaptation and mitigation together increase the avoided damage from US$ 15 to 22 Trillion (Table 13).

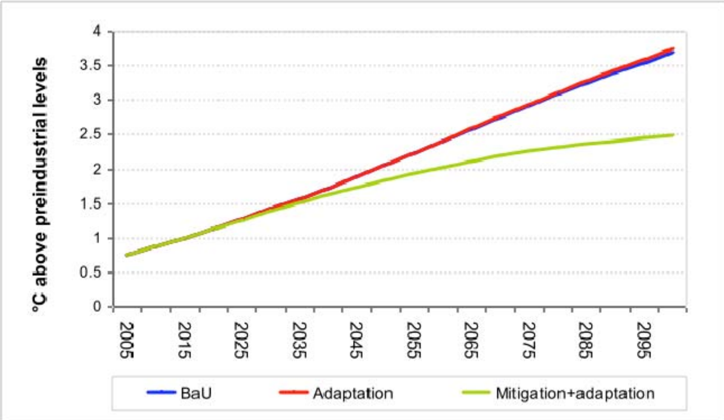
Table 13: Avoided damage (difference w.r.t. BaU) with and without mitigation (US$ Trillion, NPV 3% discounting, 2005-2100)

	WORLD	OECD	non-OECD
Mitigation + adaptation	22	6	16
Adaptation	15	3	12

There are at least two elements climate policies should deal with: the unavoidable damages due to past emissions and the additional climate change risk and vulnerabilities that can be triggered if global warming exceeds dangerous levels.

As shown in Figure 21, only ambitious mitigation policy can contain temperature increase. A policy target equal to 550 CO2-eq makes it possible to reduce global average temperature by 1.2 °C in 2100. Adaptation reduces the damage, but without influencing the temperature trend. Adaptation enables countries to grow more and experience lower damages in a world without irreversibility or discontinuity. However, it cannot prevent temperature surpassing dangerous levels. While mitigation performs well in keeping temperature increases under control, adaptation is effective at reducing residual damages.

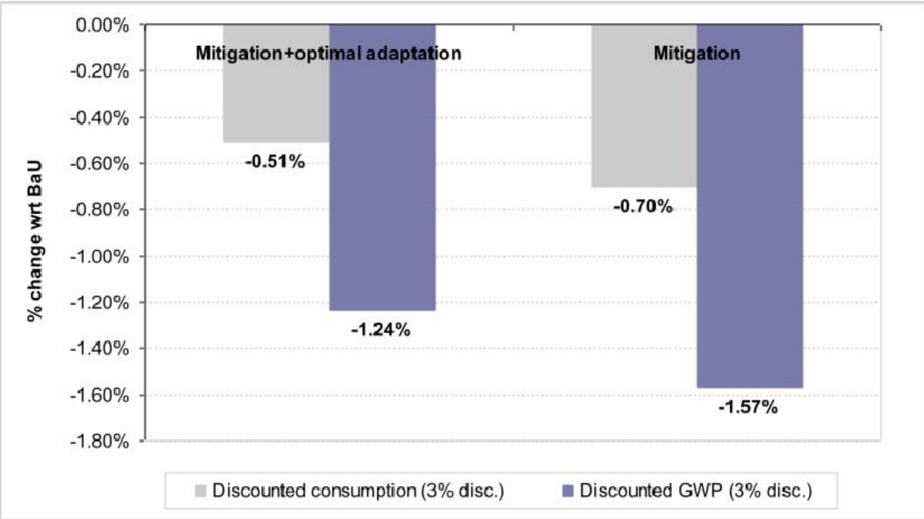
Figure 21: Contribution of adaptation and mitigation to temperature reduction



The fact that mitigation and adaptation appear as mild substitutes is the exact justification for their joint use in a cost efficient climate policy. What said is partially demonstrated by Figure 22, although the setting is that of cost-effectiveness. The macroeconomic costs of achieving a 550-CO2eq stabilisation target[11] are decreased by the welfare enhancing effect of adaptation.

[11] It should be mentioned that stabilisation costs are limited, because mitigation exploits low cost options in developed countries and low marginal abatement costs in developing countries. Moreover, a set of optimistic assumptions on technology options, timing and participation are behind these low stabilisation costs. Indeed, we implicitly assumed that the stabilisation target is achieved with full and immediate cooperation, that low carbon technology options can be deployed on a large scale and that an international carbon market is immediately available and well functioning. Bosetti et al.(2009) analysed climate policy costs when some of these assumptions are relaxed.

Figure 22: Macro-economic costs to meet a 550CO2eq stabilisation target (NPV, 3% discounting, 2005-2100)



In conclusion, the optimal climate change strategy is clearly one in which mitigation is undertaken immediately to avoid the most dangerous and potential irreversible damages from climate change. Mitigation keeps these damages below a manageable threshold. Adaptation is implemented to cope with manageable but unavoidable residual damages. Even in the presence of adaptation and a commitment to invest in it, the safe mitigation target could remain unaltered (e.g. 2°C or slightly higher).

4.3 Adaptation in IAMs: a modeling comparison

This section compares the results obtained with the AD-WITCH model with the other few models that capture the trade-off between adaptation and mitigation. Similar analyses are based on two extensions of the RICE/DICE model, namely AD-RICE and AD-DICE, as described in a previous OECD report (de Bruin et al. 2009), and the AD-FEEM-RICE model with adaptation developed by Bosello (2008).

Before looking at the results concerning adaptation and mitigation, it is useful to compare the baselines of these models. Baseline GDP and emission paths crucially affect the results, in particular policy costs.

Figure 23: Gross World Product

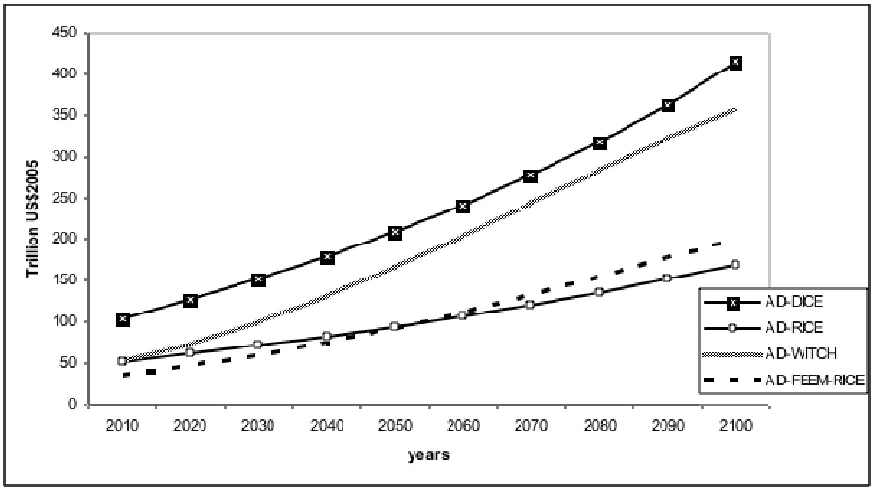
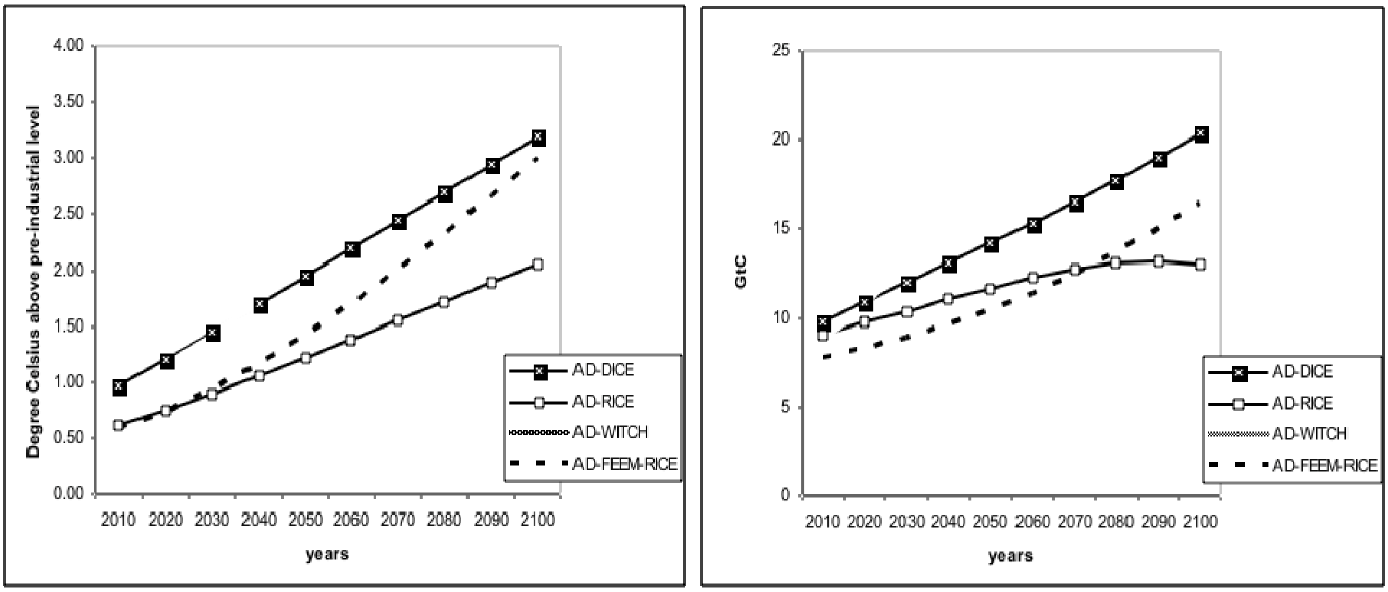


Figure 24: Temperature and CO2 emissions



Global output is shown in Figure 23. Differently from AD-DICE and AD-WITCH, the AD-RICE and the AD-FEEM-RICE models start from the non re-calibrated RICE 99 and RICE ’96 respectively. This explains their lower output. Consequently CO2 emissions, concentrations and temperature also differ (Figure 24). When compared to AD-DICE, AD-WITCH is characterised by a lower GDP, but higher emissions and temperature because its climate module is slightly different. Another important difference between models is in the solution concept. Where AD-DICE assumes full cooperation, and the internalisation of all global externalities, the other models are solved “non-cooperatively”.

Despite these differences, the models share some similarities. According to all models climate change costs, including adaptation expenditure and residual damages discounted over the century, will amount to 1% of world GDP (see Table 14).

The regional distribution of costs is comparable across models. It is characterised by higher climate change costs in developing countries such as Africa and South Asia. Lower costs occur in some high income countries, such as Canada, Japan and New Zealand (CAJAZ). Some differences emerge however. While AD-WITCH and AD-FEEM-RICE estimate positive climate change costs for Russia (TE, FSU in Table 14) and Eastern Europe (EE in AD-RICE and EEURO in AD-WITCH) AD-RICE proposes zero costs.

Table 14: Residual damage plus adaptation costs (NPV as a percentage of GDP - %)

AD-WITCH (**)		AD-FEEM-RICE (*)		AD-RICE (*)	
USA	0.3%	USA	0.6	USA	0.2
WEURO	1.3%	JPN	0.4	EUROPE	0.9
EEURO	0.7%	EU	0.7	EE	0
KOSAU	0.6%	FSU	0.3	OHI	0
CAJAZ	0.1%	CHINA	1.4	OHI/JAPAN	0
TE	0.4%	ROW	1.7	RUSSIA	0
MENA	2.3%			MI	1.1
SSA	3.8%			AFRICA	4.2
SASIA	4.1%			INDIA	4.6
CHINA	0.5%			CHINA	0.2
EASIA	1.7%			LI	2.6
LACA	1.1%			LMI	1.6
GLOBAL	1.1%		1.1	AD-DICE (*)	1.0

(*) Cooperative solution , (**) Non cooperative solution

The three models are calibrated on different data sets regarding damages. In particular AD-WITCH incorporates the more recent data on protection of water infrastructures and adjustments in energy demand for heating and cooling purposes (see Annex II).

All modelling exercises highlight that adaptation and mitigation are strategic complements. Each model stresses that their joint implementation improves welfare. Compared to the case in which only mitigation is available, adaptation increases discounted consumption by 0.24%, in AD-WITCH, by 0.3% in AD-FEEM-RICE. It increases utility by 0.3% in AD-DICE. Accordingly, an optimal climate change policy consists of a mixture of adaptation measures and investments in mitigation. This applies also in the short-term even though mitigation will only decrease damages in later periods.

Every study flags the trade-off between strategies. The introduction of mitigation decreases the need to adapt and *vice versa*. Mitigation especially in the short, medium term lowers only slightly environmental damage stock. Therefore it does little to decrease the need to adapt particularly during the first decades. Even though adaptation emerges as a powerful strategy to deal with climate change damage, irrespectively of its effectiveness, abatement is always undertaken. In the AD-WITCH model the effect of adaptation on mitigation cannot be fully captured because the stabilisation target is chosen *ex ante*.

Some important differences can be found on the time evolution of the strategic mix. In the AD-DICE simulation, adaptation is the main climate change cost reducer until 2100. Mitigation prevails afterwards. It is shown that benefits of adaptation are higher than those of mitigation until 2130.

On the contrary, AD-FEEM-RICE and AD-WITCH (even though with less emphasis) reveal that mitigation should be optimally anticipated in early periods and adaptation postponed to later stages. The first key qualitative difference with AD-DICE is that the main damage reducer in early stages is mitigation and not adaptation. Mitigation has to be anticipated because of its delayed effects driven by environmental inertia. In AD-WITCH, abatement effort and allocation is driven by the stabilisation path that has been considered which requires more mitigation during the first half of the century. Adaptation can be postponed until damage becomes really high because it is rapidly effective. A massive expenditure in adaptation is convenient when damage stock is sufficiently high.

Two other mechanisms contribute to this result. First, both in AD-WITCH and AD-FEEM-RICE protection activities provide higher benefit the larger the value at risk, approximated by GDP. As recently stressed by Parry et al. 2009, adaptation is more effective in richer societies because their willingness to pay for adaptation is larger. Increasing adaptation is implicit in rising GDP. Second, in AD-WITCH and AD-FEEM-RICE a part of adaptation expenditure does not vanish, but it cumulates over time. Therefore, adaptation is more cost-effective than in de Bruin et al. (2009) to cope with incremental damages.

These forces lead also to a different adaptation sensitivity to climate damage (see also next section). When damage becomes larger, both adaptation and mitigation increase. In AD-DICE the share of total damage reduction due to adaptation decreases. In AD-WITCH and in AD-FEEM-RICE it increases.

Finally, all exercises, apart from AD-WITCH confirm that an increased (decreased) inter-temporal preference for the future (a lower [higher] discount rate) shifts the policy emphasis to mitigation (adaptation). The different behaviour of AD-WITCH is due to the noncooperative nature of the solution. Low discounting increase the value of both future damages and consumption. In a noncooperative setting the second effect prevails because the environmental externality is not internalised.

5 Sensitivity analysis

5.1 Alternative discounting and damage functions

The optimal mix between adaptation and mitigation crucially depends on at least two main factors, namely the size of climate change damages and the pure rate of time preference. As both damages and intertemporal preferences are characterised by profound uncertainty, sensitivity analysis becomes crucial.

The climate change damage function used by the AD-WITCH model includes a reduced form relationship between temperature and gross world product. This follows closely Nordhaus and Boyer (2000), both in the functional form and in the parameter values. The resulting patterns of regional damages are in line with those depicted in Table 2. Higher losses are estimated in developing countries: in South Asia, including India, and Sub-Saharan Africa, especially because of higher damages in agriculture, from vector-borne diseases and because of catastrophic climate impacts.

Recent evidence, such as the 2007 Stern Review, UNFCCC (2007) and the IPCC Fourth Assessment Report (Parry et al. 2007; Parry et al. 2009), suggests that climate change damages may probably be higher than the values proposed by Nordhaus and Boyer (2000). Probably, the most important reason is that most IA models only partially capture non-market impacts, which are confined to the recreational value of leisure. Important climate related impacts on biodiversity and ecosystem losses or on cultural heritage are not part of the damage assessment.

AD-WITCH, as well as most IAMs, abstracts from very rapid warming and large-scale changes of the climate system (“system” surprises). As a consequence, it yields climate related impacts that, on average, are smaller than those described in studies like the 2007 Stern Review, which considers the possibility of abrupt climate changes.

The time horizon also plays a role. The longer the time horizon, the larger the observed damages become from climate change. Like most IAMs, AD-WITCH considers the dynamics of economic and climatic variables up to 2100, while, for instance, the Stern Review reaches the year 2200.

The AD-WITCH model is partly based on out-of-date evidence. Many regional estimates contained in Nordhaus and Boyer (2000) are extrapolations from studies that have been carried out for one or two regions, typically the United States.

To account for new evidence on climate-related damages and economic impacts, we have considered an alternative damage function, about twice the standard one. This new specification of the damage function yields values of damages larger than those contained in UNFCCC (2007) and close to those in Stern (2007).

Box 2. Sensitivity analysis: scenarios considered

LDAM_HPRTP : low damage – high PRTP. This is the **ADAPTATION** scenario with a discount rate set initially at 3% and then declining over time as in WITCH, DICE and RICE.

LDAM_LPRTP: low damage – low PRTP. The damage is the same as in ADAPTATION; the discount rate is 0.1% and then declining, as in the Stern Review.

HDAM_LPRTP: high damage – low PRTP. The damage is twice the damage in ADAPTATION; the discount rare is 0.1% and then declining, as in the Stern Review.

HDAM_HPRTP: high damage – high PRTP. The damage is twice the damage in ADAPTATION; the discount rate is 3% and then declining over time as in WITCH, DICE and RICE.

As suggested by Stern (2007), we have also considered two values of the pure rate of time preference (PRTP). One based on Nordhaus and Boyer (2000), equal to 3% declining over time, and a new one equal to 0.1%, as in Stern (2007). Still the AD-WITCH model does not perform a risk assessment on threshold effects or on discontinuous low probability high damage impacts, which go beyond the scope of this report[12].

This section proposes three additional scenarios, characterised by different combination of climate damage and pure rate of time preference, which are compared with the ADAPTATION scenario. The latter scenario is characterised by a lower damage and higher PRTP than the three new scenarios and it is renamed LDAM_HPRTP (see Box 2).

Figure 25 reports the time profile of residual damage in the four cases considered. In 2100, the high damage scenario is associated with a global residual damage of US$ 10 Trillion, almost twice the residual damage in the low damage scenario, which amounts to US$ 6 Trillion.

[12] However, it is likely that the general conclusions of the present study would not change. What can change is the relative weight of adaptation and mitigation in the optimal policy mix. As adaptation to catastrophic events can only be partial, and given that the probability of their occurrence can be lowered only by reducing temperature increase, mitigation could become more appealing than adaptation when the occurrence of catastrophic events is accounted for.

Figure 25: Residual damage under different discounting/damage assumptions

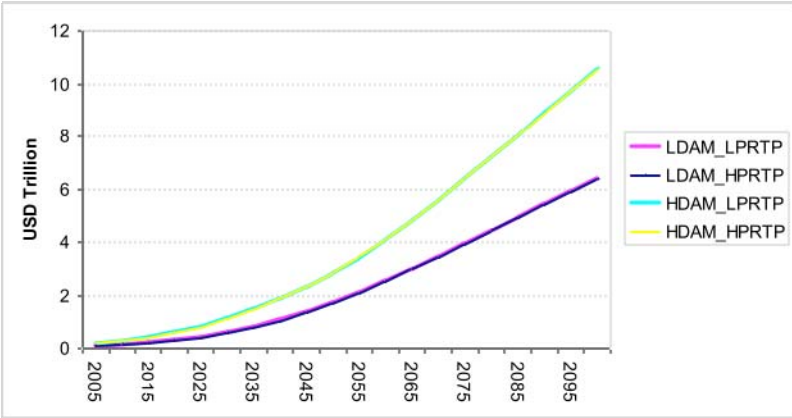


Table 15 shows variations in adaptation (adaptation expenditure) and mitigation (cumulative emissions) in the different scenarios. As expected, both higher damage and lower PRTP have the effect of increasing adaptation.

Similarly, when damages are increased, cumulative emissions become unambiguously lower and more mitigation becomes optimal. In the case of a lower PRTP, the final effect on mitigation depends on two opposing forces. On the one hand, future damages become more important and this leads to increased mitigation. On the other hand, the value of future consumption also increases. To achieve higher consumption, resources are optimally diverted away from mitigation towards investments in physical capital. Higher consumption ultimately sustains economic growth, but also increases emissions. As shown by Table 15 the second effect prevails and it is also reinforced by the presence of adaptation that makes it possible to tolerate higher emissions.

Table 16 focuses on different adaptation options in the four scenarios. A higher damage leads to an increase in all adaptation options, but with a small bias toward reactive adaptation that increases by 105% in 2100 as opposed to 97% of anticipatory adaptation and 57% of specific capacity (Table 17).

With a lower PRTP more resources are allocated to anticipatory adaptation and to building up adaptive capacity (respectively +37% and +49% in 2100), whereas reactive adaptation increases only slightly by 6%. In percentage terms, investments in specific adaptive capacity are those that increase the most (Table 17). Still this option absorbs a very small fraction of total adaptation expenditure (from 13 to 20% in 2100, depending on the case). When high damage is combined with low PRTP, the discounting effect tends to prevail and the optimal mix entails more adaptation that is slightly tilted toward stock measures, namely anticipatory adaptation and specific adaptive capacity.

Table 15: Adaptation and Mitigation under different discounting and damages

Total Adaptation Expenditure (Undiscounted – US$ Trillion)			
LDAM_HPRTP	LDAM_LPRTP	HDAM_HPRTP	HDAM_LPRTP
67	92	144	184
Residual Damage (Undiscounted - US$ Trillion)			
LDAM_HPRTP	LDAM_LPRTP	HDAM_HPRTP	HDAM_LPRTP
243	246	403	404
Cumulative emissions (GtC)			
LDAM_HPRTP	LDAM_LPRTP	HDAM_HPRTP	HDAM_LPRTP
1668	1782	1650	1741

Table 16: Adaptation under different discounting and damages

	Average annual costs (2005 US$ Billion)			
2050	LDAM_LPRTP	HDAM_HPRTP	HDAM_LPRTP	LDAM_HPRTP
Anticipatory Adaptation	186	327	490	101
Reactive Adaptation	79	227	269	48
Specific Adaptive Capacity Building	185	228	353	102
Total expenditure	450	782	1112	250
Avoided damage	329	1063	1348	194
2100	LDAM_LPRTP	HDAM_HPRTP	HDAM_LPRTP	LDAM_HPRTP
Anticipatory Adaptation	1306	1871	2510	950
Reactive Adaptation	1070	2068	2138	1007
Specific Adaptive Capacity Building	558	589	837	374
Total expenditure	2933	4527	5485	2331
Avoided damage	8198	18061	19822	7035

Table 17: Adaptation strategies compared to the base scenario in 2100 (ADAPTATION or LDAM_HPRTP)

	LDAM_LPRTP	HDAM_HPRTP	HDAM_LPRTP
Reactive Adaptation	6%	105%	112%
Anticipatory Adaptation	37%	97%	164%
Specific Adaptive Capacity Building	49%	57%	124%

Both lower PRTP and higher impacts from climate change anticipate the starting date of optimal adaption. Table 18 reports investments in specific adaptive capacity and expenditure on adaptation activities (reactive and anticipatory adaptation) in the short-run.

With high damage, already in 2010 adaptation requires US$ 0.8 Billion, 0.55 for adaptation activities and 0.28 for specific adaptive capacity. Expenditure on adaptation increases above US$ 3 Billion already in 2010 if high damage is coupled with a low PRTP. For high damage, in 2030 optimal adaptation would require between US$ 100 and 200 Billion , with high and low PRTP, respectively. Of these resources, between 16 and 22% go to specific adaptive capacity building.

Table 18: Adaptation expenditure on specific adaptive capacity and activities in the short-run (US$ Billion)

Adaptation Activities	LDAM_HPRTP	LDAM_LPRTP	HDAM_HPRTP	HDAM_LPRTP
2005	0.00	0.00	0.09	0.25
2010	0.00	0.01	0.55	2.02
2015	0.02	0.14	2.76	8.98
2020	0.19	1.04	9.88	26.13
2025	1.17	4.83	26.85	60.53
2030	4.64	14.63	60.59	121.34
Specific Adaptive Capacity Building	LDAM_HPRTP	LDAM_LPRTP	HDAM_HPRTP	HDAM_LPRTP
2005	0.00	0.00	0.05	0.15
2010	0.00	0.01	0.28	1.33
2015	0.02	0.14	1.42	6.12
2020	0.16	1.09	5.18	18.89
2025	0.97	5.06	15.16	46.84
2030	3.72	14.74	36.01	95.92

6. Concluding remarks

This study proposes an in-depth investigation of the relationships between mitigation and adaptation. It also analyses the interaction between capacity building and different adaptation activities *strictu sensu*. The analysis has been carried out using the Integrated Assessment Model AD-WITCH. We have formalised and included an adaptation module into the state-of-the-art model WITCH (Bosetti et al. 2006). Four are the main features that characterised the new version of the model:

- A detailed characterisation of the adaptation process, distinguishing between adaptive capacity building and adaptation activities. Both anticipatory and reactive measures are included;
- An updated quantitative assessment of adaptation costs and benefits at the regional level;
- An integrated specification of the effects and costs of both mitigation and adaptation within a single, game-theoretic, dynamic framework;
- A careful representation of the interactions and trade-offs between mitigation and adaptation.

The main conclusions of the this study can be summarised as follows:

I. All available adaptation options are needed to effectively control impacts of climate change. In our setting, both reactive and anticipatory measures, together with investments in adaptive capacity, are part of the optimal adaptation strategy.

II. The timing of the intervention is important. Anticipatory (or proactive) adaptation measures become effective with a delay and should be implemented first. At the equilibrium, proactive adaptation is the main adaptation strategy until 2085. Reactive adaptation prevails afterwards. This reflects the convexity of climate damage in temperature. As times goes by, there is an increasing amount of damage that cannot be accommodated with anticipatory measures. Reactive adaptation becomes the main option in the long-run.

III. There are important regional specificities. To respond to higher and earlier damages, non-OECD countries need to spend more than OECD countries on adaptation. Adaptation expenditure is concentrated on reactive interventions in non-OECD countries. This is not only driven both by the kind and evolution of damages they are confronted with, but also by their resource scarcity. Because additional investments in the developing world are particularly expensive, the most cost-effective adaptation intervention is the reactive one.

IV. Adaptation needs in developing countries are likely to be very high. Developing countries hardly have at their disposal the financial resources to finance the required adaptation expenditures. Therefore, international aid and cooperation on adaptation are necessary.

V. The introduction of adaptation decreases the need to mitigate and *vice versa*. This is the empirical and expected evidence that the two strategies (mitigation and adaptation) are strategic complements. Accordingly, both need to be part of an optimal climate policy portfolio. The possibility to adapt (mitigate) does not eliminate the need to mitigate (adapt). It also highlights the possibility to achieve welfare improvement with a careful design of the joint implementation of the two strategies. Mitigation is crucial to avoid unmanageable consequences from climate change. Adaptation is needed to deal with climate damages that cannot be avoided through mitigation. This is particularly important for developing countries. Adaptation is characterised by higher damages from climate change than developed regions. Developing countries are the ones that benefit the most from an optimal combination of the two strategies. To define a coordinated and integrated mitigation and adaptation policy mix, it is further suggested for an international North-South cooperation to combine the two strategies.

VI. The optimal response to higher climate damage is to increase resources devoted to both mitigation and to every different adaptation option. This is evidence of their complementarity. The optimal response to a decrease in the discount rate is to increase adaptation, and to decrease mitigation. On the one hand, increased weight on future climate damages call for lower emissions. On the other hand, increased weight on future consumptions, fosters economic growth and emissions. A lower discount rate also tilts the optimal adaptation mix towards "stock" strategies such as anticipatory and specific capacity.

7. References

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Annex I. Incorporating adaptation into the Witch model

Four different adaptation expenditures have been considered in the present study. Expenditure in adaptive capacity building is divided in a "generic" and a "specific" component. Expenditure in adaptation activities include proactive or anticipatory and, reactive. The starting point for the implementation is the original WITCH climate change damage function:

$$YN_{n,t} = \frac{1}{1 + CCD_{n,t}} \cdot YG_{n,t} \qquad (1)$$

In (1) damage from climate change (time and region specific) indicates a GDP loss measured by a gap between gross *YG* and net output *YN*. As in Nordhaus and Boyer (2000), the climate change damage function, $CCD_{n,t}$ is a reduced form relationship between temperature and output :

$$CCD_{n,t} = \theta_{1n} \cdot T_t + \theta_{2n} T_t^{\gamma_n} + \theta_{3n} \qquad (2)$$

Its parameters have been calibrated to replicate a percentage change in GDP loss in response to a 2.5°C temperature increase above pre industrial levels. The exponent γ is set equal to 2 to model a convex-in-temperature damage. The calibration of (2) compounds two components of climate change damage: adaptation costs and residual damages. We changed this in two ways. We   specify the role of adaptation in reducing damage in (2). We then separated the cost component of adaptation from (2). The climate change damage function with adaptation becomes:

$$CCDA_{n,t} = f(ADAPT_{n,t}, CCD_{n,t}) = \frac{1}{1 + ADAPT_{n,t}} \cdot CCD'_{n,t} \qquad (3)$$

In equation (3), an increase in adaptation activities as a whole ($ADAPT_{n,t}$) reduces the negative impact from climate change on gross output. We have chosen the simplest functional form that presents, by construction, two agreeable properties: it is bounded between 0 and 1; an infinite amount of resources allocated to adaptation can reduce the residual climate change damage to 0 at the maximum. Adaptation exhibits decreasing marginal productivity, thus additional resources to adaptation become less and less effective in reducing damage.

As mentioned before, different methods of adapting can be chosen. Total adaptation, $ADAPT_{n,t}$ is decomposed into its different forms by a sequence of Constant Elasticity of Substitution (CES) nests. The choice of the CES specification is determined by its great flexibility in representing the different degrees of substitutability and complementarity among its components. By simply adjusting the CES exponents, alternative assumptions about the relationships between different adaptation strategies can easily be tested.

A first CES nest allocates resources to adaptive capacity-building (*TCAP*) or to adaptation activities (*ACT*) according to:

$$ADAPT_{n,t} = (\alpha_{1,n} TCAP_{n,t}^{\ \rho_{ADA}} + \alpha_{2,n} ACT_{n,t}^{\rho_{ADA}})^{1/\rho_{ADA}} \tag{4}$$

Adaptive capacity-building (*TCAP*) is a CES combination of generic (*G_CAP*) and specific (*S_CAP*) adaptation capacity:

$$TCAP_{n,t} = (\alpha_{3,n} G\_CAP_{n,t}^{\ \rho_{cap}} + \alpha_{4,n} S\_CAP_{n,t}^{\rho_{tcap}})^{1/\rho_{tcap}} \tag{5}$$

Generic capacity captures every component that is not necessarily related to adaptation itself but to the economic development of a region. The underlined assumption is that the richer a region the more adaptable it is. Specific capacity depends not only on other forms of investment such as R&D for adaptation purposes and early warning systems, but also on institutional capacity.

G_CAP follows an exogenous trend mimicking the growth rate of total factor productivity. The initial value is an indicator of local capacity based on human capital and knowledge stock:

$$G\_CAP_{n,t} = G\_CAP_{n,0} * TFP(n,t) \tag{6}$$

Specific adaptive capacity building is modelled as a stock , which accumulates over time with adaptation-specific investments, $IS\_CAP_{n,t}$ according to a standard discrete-time law of motion:

$$S\_CAP_{n,t} = (1-\delta_{CAP}) \cdot S\_CAP_{n,t-1} + IS\_CAP_{n,t} \tag{7}$$

The stock depreciates at a rate of $\delta_{CAP,}$ which has been set equal to 3% per year. Investments in specific capacity have been set to be approximately 1% of world expenditure on education and total R&D in the calibration year. In absolute terms this amounts to US$ 164 Billion in 2060. This global amount has been distributed across different regions proportionally to the normalised share of education expenditure over GDP. This criteria corrects the otherwise uneven distribution of R&D investments highly concentrated in developed countries. Total adaptive capacity increases the effectiveness of adaptation activities. Adaptation activities, proactive or reactive, compose another CES nest according to:

$$ACT_{n,t} = \beta(\alpha_{6,n} PAD_{n,t}{}^{\rho_{ACT}} + \alpha_{5,n} RAD_{n,t}^{\rho_{ACT}})^{1/\rho_{ACT}} \tag{8}$$

Reactive adaptation $RAD_{n,t}$ is a flow of expenditure undertaken period by period. It deals specifically with residual damage. It indicates that the damage reduced in one period does not influence what has to be achieved in the next. On the contrary, proactive adaptation $PAD_{n,t}$ is modelled as a stock of capital. It accumulates over time with adaptation-specific investments, $IPAD_{n,t},$ according to a standard law of motion:

$$PAD_{n,t} = (1-\delta_{PAD}) \cdot PAD_{n,t-1} + IPAD_{n,t} \tag{9}$$

The stock depreciates at a rate δ_{PAD} that equals the depreciation rate of physical capital, 10% per year. Expenditure in the three adaptation measures (generic capacity is an exogenous trend) is accounted in the national income identity:

$$YN_{n,t} = C_{n,t} + I_{n,t} + IR\&D_{n,t} + \sum_{J} I_{j_{n,t}} + IS\_CAP_{n,t} + RAD_{n,t} + IPAD_{n,t} \tag{10}$$

In equation (10) expenditure in reactive adaptation, proactive adaptation, specific adaptive capacity compete with the alternative uses of income: consumption $C_{n,t}$, investment in physical capital $I_{n,t}$, investment in other forms of innovation $IR\&D_{n,t}$ and in energy technologies $I_{j_{n,t}}$.

What remains in the climate change damage function is only residual damage. Accordingly, the damage function must be defined by a new parameterisation of equation (2), which excludes adaptation costs. The calibration process of (3) and the other equations of the AD-WITCH model is described in Annex II.

Residual damage is defined as the difference between gross and net output. From equation (1) we have:

$$YG_{n,t} - YN_{n,t} = CCD_{n,t} YN_{n,t} = RD_{n,t} \tag{11}$$

Using equation (2) and equation (3), residual damage can be defined as follows:

$$RD_{n,t} = YN_{n,t} \frac{1}{1 + ADAPT_{n,t}} (\theta_{1n} T_t + \theta_{2n} \cdot T_t^{\gamma 3n} + \theta_{3n}) \tag{12}$$

Table AI.1 presents the values of the parameters that characterise the damage and adaptation functions described above.

Table AI.1. Parameters of adaptation and damage functions. Calibrated values

	USA	WEURO	EEURO	KOSAU	CAJAZ	TE	MENA	SSA	SASIA	CHINA	EASIA	LACA
θ_1	-0.0021	-0.0005	-0.0016	-0.0086	-0.008	-0.0077	0.0001	0.0003	0.0004	-0.0041	0.0003	0.001
θ_2	0.0014	0.003	0.002	0.0042	0.003	0.0037	0.0089	0.0148	0.0095	0.002	0.0037	0.003
θ_3	0.002	0.003	0.004	0.006	0.004	0.003	0	0.001	0.001	0.004	0	0.003
γ_n	2	2	1.8	2	2	2	1.6	1.6	1.8	2	2	1.1
$\alpha_{1\ (TCAP)}$	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.3	0.3
$\alpha_{2\ (ACT)}$	0.8	0.8	0.8	0.8	0.8	0.8	0.7	0.7	0.7	0.7	0.7	0.7
$\alpha_{3\ (G\_CAP)}$	0.9	0.9	0.7	0.6	0.9	0.9	0.9	0.9	0.99	0.99	0.9	0.99
$\alpha_{4\ (S\_CAP)}$	0.1	0.1	0.3	0.4	0.1	0.1	0.1	0.1	0.01	0.01	0.1	0.01
$\alpha_{5\ (RAD)}$	0.5	0.5	0.5	0.5	0.1	0.1	0.5	0.6	0.6	0.85	0.6	0.6
$\alpha_{6\ (PAD)}$	0.5	0.5	0.5	0.5	0.9	0.9	0.5	0.4	0.4	0.15	0.4	0.4
β	6	0.9	70	30	40	8	13	8	1	10	7	5

Annex II. Calibration of the AD-Witch model

Our main sources of information are Nordhaus and Boyer (2000), a OECD report (Agrawala and Fankhauser, 2008) and UNFCCC (2007). They provide the most recent and complete assessment on costs and benefits of adaptation strategies. The aforementioned studies have been integrated with area-specific modelling or assessment studies to ground our efforts for the best available quantitative knowledge.

The quantitative assessment on adaptation costs and benefits are still a work in progress and data are generally sparse. Generally in developing countries this data insufficiently provide reliable estimates. Strong inconsistencies can often be found between local and global assessments. Agrawala and Fankhauser (2008) [p.13] state, "…the few existing global multisectoral estimates face serious limitations […]. Therefore the consensus (on costs and benefits of adaptation[13]) even in order of magnitude term is premature".

The available data should be interpreted prevalently as qualitative insights on the patterns of costs and effects of adaptation in different regions, related to different strategies. As a consequence, the calibration process should aim at the ordinal rather than cardinal representation of that pattern. An extensive sensitivity analysis will then deal with the range of uncertainties.

AII.1 Proactive adaptation

AII.1.1 Coastal protection

Costs and benefits of coastal protection against climate change-induced sea level rise are the topics more deeply investigated by the adaptation literature.

In 1991 the IPCC proposed methodologies and estimates concerning the cost of sea level rise and of the benefit of coastal protection (IPCC CZMS, 1991). This issue was subsequently investigated by a very large body of literature. Studies in this vein include investigation at the world level with macro regional and country detail. With a macro-detail see for example Hoozemans et al. 1993;

[13] Italics is ours.

Fankhauser 1998; Tol 2002; 2006; Deke et al. 2002; Bosello et al. 2006; Bigano et al. 2007. For the USA, Fankhauser (1994); Yohe et al. (1996); Yohe and Schlesinger (1998) . For Europe, Nicholls and Klein (2003); CEC (2007). See also Dennis et al. (1995) for Senegal; Volonte and Nicholls, (1995) for Uruguay; Volonte and Arismendi (1995) for Venezuela; Zeider (1997) for Poland. At the site level see Gambarelli and Goria (2004) for the Fondi plane in Italy; Breil et al. (2005) for the city of Venice; Smith and Lazo (2001) for the Estonian cities of Tallin and Pärnu; for the Zhujian Delta in China; Saizar (1997) for Montevideo.

For the calibration we did not use region or country specific studies. To guarantee internal consistency to our estimates, we used the information provided by the DIVA model to assess costs and effectiveness of coastal protection. DIVA is an interactive tool that makes it possible to perform an integrated assessment of coastal zones. It is specifically designed to explore the vulnerability of coastal areas to sea level rise for different climatic and socio-economic scenarios. DIVA includes four components. The first component outlines a detailed global database with biophysical and socio-economic coastal data. The second component of DIVA observes global and regionalised climate and socio-economic scenarios until the year 2500. The third component provides an integrated model enabling the interaction between modules that assess biophysical and socio-economic impacts and the potential effects and costs of adaptation. The final component exhibits a graphical user interface for selecting data and scenarios[14].

The DIVA model can be run under an optimal protection mode. It determines, for major IPCC scenarios, the optimal level of coastal protection and its cost for each (coastal) country of the world stemming from a cost and benefit analysis based on parameterised values of land at risk and cost of different adaptation measures. The value computed for the 12 WITCH macro-regions, referring to a medium level of sea level rise related to a temperature increase of 2.5°C are reported in Table AII.1[15]. Coastal protection costs include all adaptation costs (dike building, beach nourishment and wetland nourishment). Average protection level is measured with years of protection, where maximum protection (100%) corresponds to 10000 years.

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[14] More information on the DIVA tool and the software can be found on its website http://diva.demis.nl/.

[15] More precisely we have simulated the optimal adaptation response to a sea level rise consistent with the IPCC scenario A1B-medium which foresee a temperature increase of 2.4°C and an increase in sea levels of 0.44 m.

Table AII.1. Yearly effectiveness and cost of coastal protection measures against a temperature increase of 2.5°C compared to preindustrial period and against seal level rise of 0.44 meters

	Coastal Protection Level (100 = total)	Coastal Protection Costs (Billion $)
USA	75	3.6
WEURO	54	5.0
EEURO	63	0.3
KOSAU	62	1.8
CAJAZ	37	2.9
TE	37	1.7
MENA	55	1.2
SSA	30	2.7
SASIA	47	1.3
CHINA	76	1.3
EASIA	25	4.3
LACA	46	7.7
Total		33.6

AII.1.2 Settlement and ecosystem protection

Nordhaus and Boyer (2000) report the total cost of climate change for settlements and natural ecosystems. To separate the two components four items have to be identified: protection cost and residual damage both for settlements and ecosystems.

Practically any assumption about ecosystems is highly conjectural and the available literature is of scarce support. Ecosystems cannot easily adapt to the changing climate and will often disappear, thus the adaptation potential is rather low as are adaptation costs.

We assumed that adaptation costs are a large share of total damage because human settlements can adapt at high costs. More precisely, we adaptation costs from residual damage using the proportions for coastal protections that were obtained with the DIVA model. The share of protection costs ranges from 30% in LACA to 99% in some developed regions (KOSAU).

As far as the effectiveness of this investment is concerned, we assumed it close to 90%, in protecting settlements, but as said very low (0 in fact) in protecting ecosystem. Weighting slightly more the ecosystem damage component we arbitrarily assumed that the overall protection level over settlements and ecosystems is 40%. Our estimates are reported in Table AII.2

Table AII.2: Additional expenditure (investment in infrastructure) needed to climate proof settlements against a temperature increase of 2.5°C compared to preindustrial period. Reference year 2060

	US$ Billion
USA	22
WEURO	56
EEURO	3
KOSAU	5
CAJAZ	10
TE	3
MENA	4
SSA	4
SASIA	20
CHINA	17
EASIA	4
LACA	6
Total	154

AII.1.3 Water protection

Costs of adaptation practices in the water sector for no agricultural purposes

Our reference for the assessment of the costs to adapting water infrastructures to climate change is UNFCCC (2007) based on Kirshen (2007). This last study proposes an estimate of the investment needed to meet projected water demand in 2030 consistent with the IPCC B1 and A1b scenarios in eight world regions. A drawback of this assessment is that adaptation in Kirshen (2007) is a response to both climatic and social-economic changes.

A way to disentangling the climatic from the social-economic component is suggested by UNFCCC (2007). UNFCCC assumed that 25% of additional investments are due to climate change. The remaining is used to confront social-economic changes (Table AII.3). Globally, adapting water infrastructure to climate change would require roughly US$ 180 Billion investment in 2030, 94% of which concentrated in developing countries. However, the assumption of a 25% share has no empirical basis, as observed by the recently released report (Parry et al. 2009). This item drives up adaptation expenditure especially in MENA and SSA. Assuming a lower share of 15% gives a more smooth distribution across regions. Comparing the resulting expenditures with other data, a 15% share seems more reasonable. For example, Fisher et al. (2007) estimated the costs to meet irrigation demand (infrastructure plus operating costs) between US$ 24 and 27 Billion per year by 2080. According Briscoe (1999) current spending on water infrastructure in developing countries amounts to US$ 65 Billion. For this reason we assumed a 15% share instead of 25% as suggested by UNFCCC.

Table AII.3: Expenditure needed to adapt water infrastructures to meet future water demand in 2030, IPCC B1 SRES (US$ Billion)

	Total (Climatic + Social Economic Pressures)	Due to Climatic Pressures Only in 2030 – 25% assumption	Due to Climatic Pressures Only in 2030 – 15% assumption	Due to Climatic Pressures Only in 2060*– 25% assumption	Due to Climatic Pressures Only in 2060*– 15% assumption
Africa	223	56	33	100	60
Developing Asia	230	58	35	103	62
Latin America	23	6	3	10	6
Middle East	148	37	22	66	40
OECD Europe	25	6	4	11	7
OECD North America	16	4	2	7	4
OECD Pacific	1	0	0	0	0
Transition economies	54	14	8	24	14
Total	720	180	108	321	193

Source: UNFCCC, 2007

* Our own calculations

Based on this data, first we estimated the potential total costs in 2060 shifting the 2030 data proportionally to the temperature gap between 2030 B1 temperature and our reference 2.5°C. For the regions USA, EU, CAJANZ, TE and LACA we used the regional numbers reported in Table AII.3 (4th and 5th column), scaled up to 2060. We split the data for Africa (60) between SSA, MENA and KOSAU on the basis of a vulnerability index based on Nordhaus and Boyer (200) estimates in "Other Vulnerable Markets". A similar procedure was used to split the data for ASIA (62) between SASIA, CHINA and EASIA. Finally, following Stern et al. (2007) we attribute only 30% of this expenditure to the sector "other vulnerable markets" whereas the remaining 70% has been assigned to agriculture. It refers to irrigation and water conservation-production practices in the agricultural sector.

The results of our estimates under both assumption of 15% and 25% are reported in Table AII.4. Developed countries show low adaptation costs as found in Nordhaus and Boyer (2000). Their water infrastructure are already able to contend with future climate change. The highest expenditure is expected in the Middle-East and North-Africa (MENA), followed by the South Asia (SASIA), Sub-Saharan Africa (SSA) and Transition Economies (TE).

Table AII.4: Cost of adapting water infrastructures in other vulnerable markets against a temperature increase of 2.5° compared to preindustrial period. Reference year 2060

	Other Vulnerable Markets (Billion $ -15%)	Other Vulnerable Markets (Billion $- 25%)
USA	1.3	2.1
WEURO	2	3.3
EEURO	3.2	5.3
KOSAU	2.5	4.2
CAJAZ	0.7	1.1
TE	4.3	7.2
MENA	21.7	36
SSA	5.7	9.6
SASIA	7.3	12.1
CHINA	1.3	2.1
EASIA	0.5	0.9
LACA	1.8	3.1
Total	52.3	87

Effectiveness of adaptation practices in the water sector

Several studies have been conducted on the effectiveness of adaptation in the water sector. We base our estimates on two particular studies. Kirshen et al. (2006) found that the effectiveness of adaptation can range from very low to very high values up to 100%. Effectiveness depends on the type of measure adopted. On the contrary, Callaway et. al. (2006) analysed management adaptation costs for the Berg River in South Africa. This study demonstrates the importance of a water management system, which can increase the benefits of improved water storage capacity by 40%.

We assumed that it is more difficult in developing countries to implement efficient adaptation measures and water management practices, while in developed countries it would be relatively easier to accomplish. As a consequence the effectiveness of adaptation in developed countries is assumed to be quite high, 80% (see also the study of the Rhine River by EEA, 2007), while in developing countries it is assumed to be quite low, 40%.

AII.I.4 Agriculture

Cost of adaptation practices in agriculture

The quantification of the costs of adaptation in agriculture (EEA, 2007; Agrawala and Fankhauser, 2008) is lacking in the literature on adaptation. This is mostly because a large part of agricultural adaptation practices are implemented at the farm level. The farmers decide “autonomously” without the direct intervention of public agencies. This suggests long-term planning and investment activities. Typical examples of these practices are seasonal adjustments in the crop mix or timing which in the literature are assumed to entail very low if not zero costs.

The most significant cost component of climate change adaptation in agriculture is presumably related to the improvement of irrigation, or water conservation systems. These are forms of adaptation that can be classified as proactive. As already mentioned, we assigned 70% of adaptation costs on water infrastructure extrapolated from UNFCCC (see Table AII.3) to the agricultural sector. The results of our estimates under both assumption of 15% and 25% are reported in Table AII.5.

Table AII.5: Cost of adapting water infrastructures in other vulnerable markets against a temperature increase of 2.5°C compared to preindustrial period. Reference year 2060

	Agriculture (irrigation) (Billion $) (15%)	Agriculture (irrigation) (Billion $) (25%)
USA	3	5
WEURO	4.7	7.8
EEURO	7.4	12.3
KOSAU	5.9	9.8
CAJAZ	1.6	2.7
TE	10.1	16.9
MENA	50.7	84.1
SSA	13.4	22.3
SASIA	17	28.3
CHINA	3	4.9
EASIA	1.3	2.1
LACA	4.3	7.2
Total	122.4	203.4

Higher costs are estimated for some developing countries, namely Middle East and North Africa, South Asia and Sub-Saharan Africa. Among developed regions, only in Eastern Europe (EEURO) costs are significant, essentially because of the relevance of the agricultural sector. It is also highly vulnerable to climate change. Transition economies is another region in which agriculture plays a major role and features relatively high costs.

Effectiveness of adaptation practices in agriculture

The literature on the effectiveness of climate change adaptation practices in agriculture respect both their impact on land productivity or on farmers' income is broad and dates back to the early 90's (Kane et al. 1992; Fisher et al. 1993; Reilly et al. 1994; Rosenzweigh and Parry 1994). Subsequently, the Working Group II of the IPCC contributed with specific chapters on impacts and adaptation in agriculture both in Third (IPCC 2001) and in the Fourth (IPCC 2007) Assessment Reports. Surveying this literature (for a non exhaustive list see Rosenzweigh and Hillel 1998; Antle et al. 2001; Tan and Shibasaky 2003, Easterling et al. 2007), a rough estimate of the effectiveness of adaptation in agriculture ranges between 40% and 98% of total climatic damage for a doubling of

CO_2 concentration. Such a wide range is determined by the country or site-specific characteristic of the study, the crop investigated, the modelling approach, and the assumptions on adaptation practices available.

This makes it quite difficult to summarise in just one consistent value adaptation effectiveness encompassing all possible agricultural practices, especially referred to wide regional aggregates like those of the WITCH model. We have chosen to refer to only one study, specifically Tan and Shibasaky (2003). They provide estimates of changes in crop yields for six world macro-regions (Asia, North America, South America, Europe, Australia, Africa) with and without adaptation in 2050. These differences in yields can be considered representative of the effectiveness of farmers' adaptation practices. When a WITCH region falls inside a Tan and Shibasaky aggregate, we assigned to that region the same value reported by their study. When a WITCH region falls over two Tan and Shibasaky aggregates, we assigned to that region an average of the values reported by their study. Table AII.6 reports the resulting protection levels for the WITCH regions.

Table AII.6. Effectiveness of adaptation practices in agriculture against a temperature increase of 2.5°C compared to preindustrial period. Reference year 2060

	Reduced damage (1=100%)
USA	0.48
WEURO	0.43
EEURO	0.43
KOSAU	0.27
CAJAZ	0.38
TE	0.38
MENA	0.33
SSA	0.23
SASIA	0.33
CHINA	0.33
EASIA	0.33
LACA	0.38

Source: Tan & Shibasaki (2003) and own calculations for the extension to the WITCH regions

AII.2 Reactive adaptation

AII. 2.2 Health

Cost of adaptation in the health sector

Many studies describe the possible adaptation strategies that can be implemented by health sectors in developed and developing countries (WHO 2005; WHO 2006). Nevertheless, very few researches try a quantitative cost assessment of these measures. The problem here is double: first there is a general lack of information concerning the potential costs of some interventions. Second, it is very difficult conceptually and practically to separate the costs of adaptation to changes in health status induced by climate change from those related to change in health status *per se.* Agrawala and Fankhauser (2008) report just one study, EBI (2007), that estimates the treatment costs of additional number of cases of diarrhoeal diseases, malnutrition and malaria related to climate change. The additional cost for the world as a whole ranges between US$ 4 and 12.6 Billion by 2030.

In our assessment we instead refer to Tol et al. (2001) which assesses the treatment cost associated to malaria, dengue, schistosomiasis, diarrhoeal, cardiovascular and respiratory diseases, for different scenarios of temperature increases, for all countries of the world. We rescaled his information to our temperature scenario of 2.5°C and we aggregated the data according to WITCH regional aggregation. Results are reported in Table AII.7.

Table AII.7. Additional treatment costs for climate related diseases against a temperature increase of 2.5°C compared to preindustrial period. Reference year 2060

	Disease Treatment Costs (Billion $)
USA	1.1
WEURO	-0.7
EEURO	-0.1
KOSAU	1.9
CAJAZ	3.0
TE	0.1
MENA	2.1
SSA	0.5
SASIA	1.1
CHINA	0.3
EASIA	4.7
LACA	5.7
Total	20.6

Developing regions are more adversely affected by climate change impacts on health than developed ones, accordingly they have to spend more in diseases' treatment. This is driven by the overwhelming effect of vector born diseases, above all malaria, which are almost unknown in developed regions. In European regions, the decreased morbidity due to cold-related diseases more than compensates the increased morbidity of hot related diseases. This explains the negative treatment costs in those regions.

The total treatment cost, roughly US$ 20 Billion, is higher than that reported by EBI (2007), for two reasons. First, additional diseases are included in Tol et al. (2001). Second, the climate scenario considered in Tol et al. (2001) is worse than that analysed by EBI (2007) .

Effectiveness of adaptation in the health sector

Effectiveness of adaptation measures in the health care sector is even more controversial. For vector borne diseases our references is the World Malaria Report (WHO 2008). The study proposes a protection level quite low for developing countries that are affected primarily by vector borne diseases. Protection levels range from 20% in Africa to 40% in other non OECD countries.

Although we do not have data on developed regions, we assume that their protection levels, also considering financial resources, are much higher, ranging from the 60% to the 90%. Table AII.8 summarises our estimation.

Table AII.8. Effectiveness of adaptation practices in the health sector against a temperature increase of 2.5°C compared to preindustrial period. Reference year 2060

	Reduced damage (1=100%)
USA	0.90
WEURO	0.90
EEURO	0.60
KOSAU	0.81
CAJAZ	0.69
TE	0.70
MENA	0.60
SSA	0.20
SASIA	0.35
CHINA	0.40
EASIA	0.40
LACA	0.90

AII.2.3 Space Heating and Cooling

Cost of adaptation for space heating and cooling

In the present research the change in the heating and cooling expenditure has been considered as a proxy of adaptation costs in the energy sector. Only the demand side is taken into account here.

There are several country level studies which identify the relationship between temperature and energy demand, but in our knowledge there are only three studies that estimated the effects of climate change on the demand for energy at the global level, namely Tol (2002; 2002a), Bigano et al. (2006), De Cian et al. (2007).

Tol (2002; 2002b) based his extrapolations on a UK-specific model that relates the energy used for heating or cooling to degree days, per capita income, and energy efficiency. Climatic change is likely to affect the consumption of energy via decreases in the demand for space heating and increases in demand for cooling. He hypothesised that both relationships are linear. Economic impacts were derived from energy price scenarios and extrapolated to the rest of the world. Energy efficiency is assumed to increase, lessening costs. According to these studies, benefits (reduced heating) are about 0.75% of GDP in 2100 and damages (increased cooling) are approximately 0.45%. The global savings from reduced demand for heating remain below 1% of GDP through 2200. However, by the 22nd century, they begin to level off because of increased energy efficiency. For cooling, the additional amount spent rises to just above 0.6% of GDP by 2200. Thus throughout the next two centuries, net energy demand decreases.

These findings are confirmed by Bigano et al. (2006). They conducted a dynamic panel data econometric estimation of the demand for coal, gas, electricity, oil and oil products by residential, commercial and industrial users in OECD and (a few) non-OECD countries. They derive long-run elasticities for temperature. The main findings highlighted that residential demand responds negatively to temperature increases, pointing at a prevalence of heating needs in determining residential demand. By contrast, industrial demand is insensitive to temperature increases. In the case of the service sector, only electricity demand displays a mildly significant negative elasticity to temperature changes. The estimated elasticities range from the –0.6 of electricity to the -3 for oil product. This study however neither considers seasonality effects nor differentiate among countries in different climatic areas.

These features are introduced by De Cian et al. (2007) which estimate the elasticity of energy demand to temperature for different energy vectors (oil, gas, electricity) differentiating among hot, mild, and cold regions. The study covers all developed countries, but few developing (the most prominent is India). It also refers only to households' energy consumption patterns, as the industry energy consumption did not appear to be significantly affected by climate change. Due to its geographical detail and the more satisfactory econometric specification we decided to use De Cian et al. (2007) elasticities in the present assessment.

Whenever possible, they have been used to compute the energy demand changes corresponding to a 2.5°C increase for the corresponding WITCH regions. The subsequent economic cost has been calculated pricing the change in quantity of energy consumed with prices reported by International Energy Agency. For the WITCH regions not covered by De Cian et al. (2007), we used reasonable averages of the available data. Changes in expenditure are reported in Table AII.9

Table AII.9. Change in energy expenditure for space heating and cooling against a temperature increase of 2.5°C compared to preindustrial period. Reference year 2060

	US$ Billion
USA	3.9
WEURO	-8.8
EEURO	-0.8
KOSAU	7.7
CAJAZ	-7.8
TE	0.6
MENA	18.6
SSA	10.4
SASIA	50.7
CHINA	45.5
EASIA	25.9
LACA	2.0
Total	148.0

According to De Cian et al. (2007) household energy expenditures are projected to increase at the world level. This outcome results from the composition of two different effects. Energy use increases typically in hot and (richer regions, above all in Middle East and North Africa, while it decreases in the EU15 and in the Canada – Japan - Australia and New Zealand aggregates. In the first case, the increased households summer energy expenditure for conditioning more than compensate the decreased need for winter heating. The opposite happens in large colder regions such as North European ones or Canada. Here the decreased heating needs during colder seasons more than compensate the increased cooling demand during the summer.

Effectiveness of adaptation heating and cooling

Space cooling has a great potential to decrease indoor thermal discomfort and is of relatively easy implementation, therefore we assume its protection potential to be high, 80% in developed countries. We assumed it to be lower, even half, in developing countries essentially because of lower availability of cooling and heating facilities.

AII.3 General and specific adaptive capacity

Generic capacity captures all components not necessarily related to adaptation itself but to the economic development of a region. The underlined assumption is that the richer a region the more adaptable it is. Generic capacity is assumed to evolve exogenously with the growth rate of total factor productivity. The initial value is an indicator of local capacity based on human capital and knowledge stock. It is computed using data on education and R&D expenditure by World Development Indicators (2008). As a consequence, initial general capacity is larger in developed regions, but growth rates are higher in developing ones. Table AII.10 shows the initial level of generic capacity.

Table AII.10. Initial level of generic capacity

Year 2005

	US$ Trillion
USA	9.03
WEURO	10.74
EEURO	0.30
KOSAU	0.83
CAJAZ	4.32
TE	0.40
MENA	0.69
SSA	0.05
SASIA	0.25
CHINA	0.32
EASIA	0.20
LACA	1.24
Total	28.36

Specific capacity includes all forms of expenditure, investments, and institutions that could increase the adaptive capacity of a system and thus make adaptation activities more effective in reducing climate change damages. Examples of investments that could fall within this category are meteorological services, climate modelling and impact assessment, agricultural extension, innovation for adaptation purposes, and early warning systems, etc.

When calibrating this variable, we face a severe data constrain problem. The only activities we have data on are innovation in the agricultural sector and implementation of early warning systems.

Agriculture and health are probably the sectors in which innovation is likely to play a particularly important role in the development of new and more effective adaptation responses. However, studies on the application of new inventions to adaptation purposes is still at a very early stage. To our knowledge, only UNFCCC (2007) provides global estimates for the additional expenditure on innovation in agriculture, for developing and developed regions, for a total of 2000 US$ 5.420 Million.

Early warning systems can be considered an anticipatory adaptation measure that makes it possible to reduce the potential impact of climate change. Their cost can also be considered a particular investment that builds an adaptation stock whose benefits will last more than 1 period.

Adams et al. (2000) founds that the benefits of an ENSO early warning system for Mexico is approximately US$ 10 million annually. Benefits are measured as the saved costs for the agricultural sector that can plan in advance crop timing and mix. The cost assessed by Adams et al. (2000) amount to US$ 5 Million. If only these two forms of specific capacity were considered, specific capacity would probably be heavily underestimated because many other items would be excluded. For this reason, we decided to calibrate investments in specific capacity as a share of total world expenditure on education and total R&D[16].We set the share to an arbitrarily low value, about 1% which corresponds to US$ 164 Billion in 2060. This global amount has then be distributed to the different regions according to the normalized share of education expenditure over GDP.

[16] Data on R&D and education expenditure are from World Development Indicators, 2008.

Table AII.11. Investments in specific adaptive capacity against a temperature increase of 2.5°C compared to preindustrial period. Reference Year 2060

	AD-WITCH (US$ Billion)
USA	11
WEURO	31
EEURO	1
KOSAU	2
CAJAZ	2
TE	2
MENA	21
SSA	6
SASIA	34
CHINA	17
EASIA	18
LACA	19
Total	164

Annex III. The WITCH model update

The WITCH model developed by the climate change group at FEEM (Bosetti et al. 2006; Bosetti et al. 2007) is an energy-economy-climate model designed to explicitly deal with the main features of climate change. It is a regional model in which the noncooperative nature of international relationships is explicitly accounted for. It is a truly intertemporal optimization model, with a long term horizon covering all century until 2100. The regional and intertemporal dimensions of the model make it possible to differentiate climate policies across regions and over time. Finally, the model includes a wide range of energy technology options, with different assumptions on their future development, which is also related to the level of innovation effort undertaken by countries.

The core structure of the model is described at length in the technical report (Bosetti et al., 2007). The focus of this Annex is on the new elements of the latest version used in this report, and in particular on the Adaptation module of WITCH.

Overall model structure

WITCH is a dynamic optimal growth general equilibrium model with a detailed ("bottom-up") representation of the energy sector, thus belonging to a new class of hybrid (both "top-down" and "bottom-up") models. It is a global model, divided into 12 macro-regions.

The world economy is indeed disaggregated into twelve macro regions: USA (United States), WEURO (Western Europe), EEURO (Eastern Europe), KOSAU (Korea, South Africa, Australia), CAJANZ (Canada, Japan, New Zealand), TE (Transition Economies), MENA (Middle East and North Africa), SSA (Sub-Saharan Africa), SASIA (South Asia), CHINA (China and Taiwan), EASIA (South East Asia), LACA (Latin America, Mexico and Caribbean). This grouping has been determined by economic, geographic, resource endowment and energy market similarities.

The model proposes a bottom-up characterisation of the energy sector. Seven different energy-generating technologies are modelled: coal, oil, gas, wind & solar, nuclear, electricity, and biofuels. Their penetration rate is driven also by endogenous country and sector specific innovation. The model distinguishes between dedicated R&D investments for enhancing energy efficiency from investment aimed at facilitating the competitiveness of innovative low carbon technologies in both the electric and non-electric sectors (backstops). R&D processes are subject to stand on shoulders as well on neighbours effects. Specifically, international spillovers of knowledge are accounted for to mimic the flow of ideas and knowledge across countries. Finally, experience processes through Learning by Doing are accounted for in the development of niche technologies such as renewable energy (Wind&Solar) and the backstops. Through the optimisation process regions choose the optimal dynamic path of different investments, namely in physical capital, in R&D, energy technologies and consumption of fossil fuels.

We updated the model base year to 2005, and use the most recent estimates of population growth. The annual estimates and projections produced by the UN Population Division are used for the first 50 years[17]. For the period 2050 to 2100, the updated data is not available, and less recent long term projections, also produced by the UN Population Division[18,] are adopted instead. The differences in the two datasets are smoothed by extrapolating population levels at 5 year periods for 2050-2100, using average 2050-2100 growth rates. Similar techniques are used to project population trends beyond 2100.

The GDP data for the new base year are from the World Bank Development Indicators 2007, and are reported in US$ 2005 . We maintain the use of market exchange rates (MER). World GDP in 2005 equals to US$ 44.2 Trillion. Although GDP dynamics is partly endogenously determined in the WITCH model, it is possible to calibrate growth of different countries by adjusting the growth rate of total factor productivity, the main engine of macroeconomic growth.

The prices of fossil fuels and exhaustible resources have been revised, following the dynamics of market prices between 2002 and 2005. Base year prices have been calibrated following Enerdata, IEA WEO2007 and EIA AEO2008.

Climate Module and GHG Emissions

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[17] Data are available from http://unstats.un.org/unsd/cdb/cdb_simple_data_extract.asp?strSearch=&srID=13660&from=simple.

[18] UN (2004), World Population to 2300, Report No. ST/ESA/SER.A/236, Department of Economic and Social Affairs, Population Division, New York.

We continue to use the MAGICC 3-box layer climate model[19] as described in Nordhaus and Boyer (2000). CO_2 concentrations in the atmosphere have been updated to 2005 at roughly 385ppm and temperature increase above pre-industrial at 0.76°C, according to IPCC 4AR (2007). Other parameters governing the climate equations have been adjusted following Nordhaus (2007)[20]. We have replaced the exogenous non-CO_2 radiative forcing in equation with specific representation of other GHGs and sulphates. The damage function of climate change on the economic activity is left unchanged.

In this version of WITCH we maintain the same initial stoichiometric coefficients as in previous versions. However, to differentiate the higher emission content of non-conventional oil as opposed to conventional ones, we link the carbon emission coefficient for oil to its availability. Specifically, the stoichiometric coefficient for oil increases with the cumulative oil consumed so that it increases by 25% when 2000 Billions Barrels are reached. An upper bound of 50% is assumed. The 2000 figure is calibrated on IEA 2005[21] estimates on conventional oil resource availability. The 25% increase is chosen given that estimates[22] range between 14% and 39%.

Non-CO_2 GHGs are important contributors to global warming, and might offer economically attractive ways of mitigating it[23]. Previous versions of WITCH only considers explicitly industrial CO_2 emissions, while other GHGs, together with aerosols, enter the model in an exogenous and aggregated manner, as a single radiative forcing component.

In this version of WITCH, we take a step forward and specify non-CO_2 gases, modelling explicitly emissions of CH_4, N_2O, SLF (short lived fluorinated gases, i.e. HFCs with lifetimes under 100 years) and LLF (long lived fluorinated, i.e. HFC with long lifetime, PFCs, and SF6). We also distinguish SO_2 aerosols, which have a cooling effect on temperature.

Since most of these gases are determined by agricultural practices, we rely on estimates for reference emissions and a top-down approach for mitigation supply curves. For the baseline projections of non-CO_2 GHGs, we use EPA regional estimates[24]. The regional estimates and

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[19] Wigley, T.M.L. 1994. MAGICC (Model for the Assessment of Greenhouse-gas Induced Climate Change): User's Guide and Scientific Reference Manual. National Center for Atmospheric Research, Boulder, Colorado.
[20] http://nordhaus.econ.yale.edu/DICE2007.htm
[21] IEA 2005, Resources to Reserves – Oil & Gas Technologies for the Energy Markets of the Future
[22] Farrell and Brandt, 2005
[23] See the Energy Journal Special Issue (2006) (EMF-21), and the IPCC 4ar WG III (IPCC, 2007)
[24] EPA Report 430-R-06-003, June 2006. the report is available from: http://www.epa.gov/climatechange/economics/mitigation.html.

projections are available until 2020 only: beyond that date, we use growth rates for each gas as specified in the IIASA-MESSAGE-B2 scenario[25], that has underlying assumptions similar to the WITCH ones. SO_2 emissions are taken from MERGE v.5[26] and MESSAGE B2: given the very large uncertainty associated with aerosols, they are translated directly into the temperature effect (cooling), so that we only report the radiative forcing deriving from GHGs. In any case, sulphates are expected to be gradually phased out over the next decades, so that eventually the two radiative forcing measure will converge to similar values.

The equations translating non-CO_2 emissions into radiative forcing are taken from MERGE v.5. The global warming potential (GWP) methodology is employed, and figures for GWP as well as base year stock of the various GHGs are taken from IPCC Fourth Assessment Report, Working Group I. The simplified equation translating CO_2 concentrations into radiative forcing has been modified from WITCH06 and is now in line with IPCC[27].

We introduce end-of-pipe type of abatement possibilities by marginal abatement curves (MACs) for non-CO_2 GHG mitigation. We use MAC provided by EPA for the EMF 21 project[28], aggregated for the WITCH regions. MAC are available for 11 cost categories ranging from 10 to 200 US$/tC. We have ruled out zero or negative cost abatement options. MAC are static projections for 2010 and 2020, and for many regions they show very low upper values, such that even at maximum abatement, emissions would keep growing over time. We thus introduce exogenous technological improvements: for the highest cost category only (the 200 US$/tC) we assume a technical progress factor that reaches 2 in 2050 and the upper bound of 3 in 2075.

We however set an upper bound to the amount of emissions which can be abated, assuming that no more than 90% of each gas emissions can be mitigated. Such a framework enables us to keep non-CO_2 GHG emissions somewhat stable in a stringent mitigation scenario (530e) in the first half of the century, and subsequently decline gradually. This path is similar to what is found in the CCSP report[29], as well as in MESSAGE stabilisation scenarios. Nonetheless, the very little evidence on technology improvements potential in non-CO_2 GHG sectors indicates that sensitivity analysis should be performed to verify the impact on policy costs.

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[25] Available at http://www.iiasa.ac.at/web-apps/ggi/GgiDb/dsd?Action=htmlpage&page=regions
[26] http://www.stanford.edu/group/MERGE/m5ccsp.html
[27] http://www.grida.no/climate/ipcc_tar/wg1/222.htm, Table 6.2, first Row
[28] http://www.stanford.edu/group/EMF/projects/projectemf21.htm
[29] http://www.climatescience.gov/Library/sap/sap2-1/finalreport/default.htm

Technological Innovation

WITCH is enhanced by the inclusion of two backstop technologies that require dedicated innovation investments to become economically competitive, even in a scenario with a climate policy. We follow the most recent characterisation in the technology and climate change literature, modelling the costs of the backstop technologies with a two-factor learning curve in which their price declines both with investments in dedicated R&D and with technology diffusion. This improved formulation is meant to overcome the main criticism of the single factor experience curves[30] by providing a more structural -R&D investment led- approach to the penetration of new technologies, and to ultimately better inform policy makers on the innovation needs in the energy sector. More specifically, we model the investment cost in a backstop technology as being influenced by a Learning by Researching process (main driving force before adoption) and by Learning by Doing (main driving force after adoption), the so called 2 factor learning curve formulation[31].

We set the initial prices of the backstop technologies at roughly 10 times the 2005 price of commercial equivalents (16,000 US$/kW for electric, and 550 US$/bbl for non-electric). The cumulative deployment of the technology is initiated at 1000twh and 1000EJ respectively for the electric and non-electric, an arbitrarily low value[32]. The backstop technologies are assumed to be renewable in the sense that the fuel cost component is negligible; for power generation, it is assumed to operate at load factors comparable with those of baseload power generation.

Backstops substitute linearly nuclear power in the electric sector, and oil in the non-electric one. We assume that once the backstop technologies become competitive thanks to dedicated R&D investment and pilot deployments, their uptake will not be immediate and complete, but rather there will be a transition and adjustment period. The upper limit on penetration is set equivalent to 5% of the total consumption in the previous period by technologies other than the backstop, plus the plus the electricity produced by the backstop itself.

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[30] Nemet, 2006
[31] Kouvaritakis et al., 2000
[32] Kypreos, 2007.